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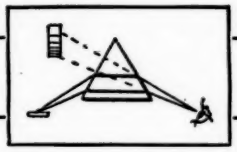

DECEMBER
1936



**Subscriptions to *The Review of Scientific Instruments*** . . A. C. HARDY 427

**Filters for the Infrared** . . R. BOWLING BARNES AND LYMAN G. BONNER 428

**Transmissions of Powder Films to the Infrared Spectrum** . . . . . JESSE H. PLUMMER 434

**Electric Welsbach Lamp** . . . . . A. H. PFUND 439

**Polarimetric Determination of Optical Properties**. RICHARD M. EMBERSON 443

**Simple Azimuth and Phase Half-Shade of Variable Sensitivity** . C. V. KENT 450

**Polaroid Half-Shade Analyzer** . . . . . A. H. PFUND 453

**Author Index to Volume 26** . . . . . 454

**Analytic Subject Index to Volume 26** . . . . . 457



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## Subscriptions to *The Review of Scientific Instruments*

WHEN, beginning with January, 1936, the American Institute of Physics found it necessary to place *The Review of Scientific Instruments* on a subscription basis, the Board of Directors of the Optical Society agreed that the members of the society, who since 1922 had received *The Review* in partial return for membership dues, had a justifiable expectation that they might continue to receive *The Review* during 1936. Accordingly the Board of Directors at its October, 1935, meeting voted to purchase from the American Institute a block of subscriptions to *The Review of Scientific Instruments* for 1936 so that each member of the society in good standing should receive *The Review* for that year without charge. Announcement to this effect was made in an editorial in the December, 1935, issue of the *Journal of the Optical Society of America*. It was stated at that time that the arrangement was made for 1936 only.

The question of continuing the block of subscriptions to *The Review of Scientific Instruments* for members of the Optical Society was discussed at length by the Board of Directors at its recent meeting. It was unanimously agreed by the Board that, the expectations of the members of the society with regard to receiving *The Review of Scientific Instruments* during the transition period having been met, the Optical Society's relations to *The Review of Scientific Instruments* should be the same as that of other member societies of the Institute and accordingly it was decided to discontinue the block-subscription plan.

The subscription rate to *The Review of Scientific Instruments* is $3.00 for non-members and $1.50 for members of Founder Societies of the Institute. It is hoped that members of the Optical Society will take advantage of this special rate and continue their subscriptions to *The Review*. *The Review*, being an official journal of the American Institute of Physics, contains articles and other material of interest to all physicists whatever their respective professional affiliations or fields of specialization.

A. C. HARDY
*President of the Optical Society of America*



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# Filters for the Infrared

R. BOWLING BARNES* AND LYMAN G. BONNER,** *Palmer Physical Laboratory, Princeton University, Princeton, N. J.*

(Received October 26, 1936)

A simple filtering system, involving the use of only two simply constructed selenium powder filters, is described, by the use of which it is possible to obtain a pure energy spectrum with a wire grating spectrometer in the region 40–130$\mu$. In addition transmission curves are given for a number of substances in the regions 1–15$\mu$ and 35–130$\mu$.

IN operating a grating spectrometer in the infrared, one of the most difficult and troublesome problems encountered is that of eliminating, in a given wave-length region, overlapping orders of shorter wave-lengths. In this work we were principally concerned with developing methods for use in the far infrared, beyond $\lambda = 40\mu$, but many of the filters developed should be quite useful for work in the short wave infrared. Most of the development work was done with a wire grating spectrometer, which has been described elsewhere,[1] though we had also available a rocksalt prism instrument[2] for comparison measurements in the region 1–15$\mu$. The characteristics of the spectrometer, namely that, as a result of the equality of the diameter of the wire and the width of the aperture in the grating, even orders were missing, and further, that the presence of 0.7 mm of crystal quartz in the light path caused almost complete opacity for wave-lengths between 5.5 and 38$\mu$, made it an ideal instrument for investigating the effects of high orders of short wave-lengths in the far infrared. Another factor contributing to the elimination of short wave-length energy was the nature of the emission spectrum of the Welsbach mantle used as a source. As is well known this spectrum consists almost entirely, in the near infrared, of two emission peaks of the gas flame used to excite the mantle; namely the $H_2O$ peak at 2.75$\mu$ and the $CO_2$ peak at 4.35$\mu$, with a small amount of black-body emission on the short wave side of the $H_2O$ peak. It is not until beyond about 6 or 7$\mu$ that the emission of the mantle itself begins to become important, and by the time a wave-length of 15 or 20$\mu$ is reached this emission is nearly equal to that of a black-body at a temperature estimated to be about 1800°Abs. Fig. 1 shows the emission curve of the Welsbach mantle used, as obtained on the rocksalt spectrometer, while Fig. 2 shows the same emission curve run on the grating instrument. It can be seen that the first peak, that of $H_2O$, has been considerably broadened, shifted and increased in intensity by the effect of overlapping orders, while the third orders of the two peaks show up quite clearly. A transmission curve taken on the crystal quartz windows present in the light path showed complete opacity beyond 5.5$\mu$. Any energy obtained beyond that point on the grating instrument was, without doubt, high orders of lower wave-length energy. Experiments to be discussed later showed definitely that very high orders (20th–50th) of this energy below 5.5$\mu$ could account for a considerable fraction of the deflection obtained even at 200$\mu$.

Since, in our present problem, even orders were absent and the quartz cut out all wave-lengths between 5.5 and 38$\mu$, it should be possible to work to $3\times40$, or 120$\mu$ simply by finding a filter which would effectively remove all radiation below 5.5$\mu$. Powder filters,[3] wherein the transmission limits are determined by the size of the particle, seemed most likely to succeed, and several types were investigated. Quartz powder, separated by the method recently described,[4] was first tried, and though it was found that the near infrared transmission could be regulated in a satisfactory manner, the characteristic absorption of quartz in the far infrared was too strong to permit of their use. Another convenient

* Now with the American Cyanamid Company, Stamford, Conn.

** National Research Fellow.

[1] R. B. Barnes, Rev. Sci. Inst. **5**, 237 (1934).

[2] R. B. Barnes, R. R. Brattain and F. Seitz, Phys. Rev. **48**, 582 (1935).

[3] Filters of this type were first described by Pfund (A. H. Pfund, Phys. Rev. **36**, 71 (1930)).

[4] R. B. Barnes and L. G. Bonner, Phys. Rev. **49**, 732 (1936).

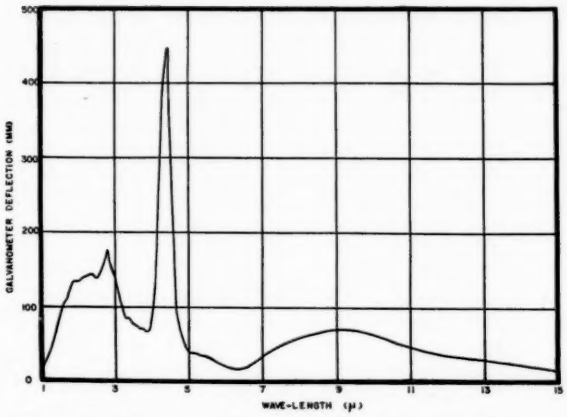



FIG. 1. Emission curve of a Welsbach mantle excited by a gas flame, as obtained on the rocksalt spectrometer.

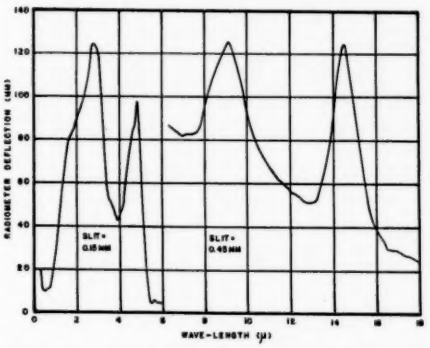



FIG. 2. Emission curve of the same mantle shown in Fig. 1, as obtained on the wire grating instrument. The slit width was increased at 6μ in order to bring out more clearly the third-order peaks.

powder filter consists of MgO prepared by condensing the fumes from burning magnesium ribbon on a suitable surface, in this case a thin film of nitrocellulose. The particle size and hence the lower transmission limit may be varied roughly by adjusting the height of the surface above the flame. For our experiments nitrocellulose films were prepared and mounted on brass frames in the usual way. To prevent burning of the film, the frame was inverted, filled with water, and could then be held right in the magnesium flame if desired without danger of burning the film. After a sufficiently thick coat of the MgO had been deposited the water was poured out and the film permitted to dry. These powder layers were then examined in the rocksalt spectrometer. Fig. 3 gives a series of such curves for powders prepared at various heights above the flame. As may be seen it was found impossible to prepare a filter that was truly opaque beyond about 3.5μ, so that these would not be suitable for the present filtering problem. However, it is important to notice that, for most of these filters, the breaks between opacity and high transmission are quite sharp, the transmissions being, for the most part, up to quite reasonable percentages within the octave. The filters should prove very suitable for echelette grating work within this limited range. The small dips in the curves are due mostly to true absorption of the nitrocellulose film, although the MgO itself becomes nearly opaque at about 14μ. Later curves will show that these MgO filters are, however, quite transparent in the far infrared.

Pfund[5] has demonstrated that various metals can be deposited in a finely divided form, simply by distillation from a hot filament under suitable pressure conditions, and that the average particle size may be regulated by varying the pressure, higher pressures favoring larger particles. Selenium seemed to be the most convenient of the suitable metals, so a series of experiments was performed on layers of distilled Se powder. The procedure for preparation of these powders was exactly that described by Pfund, a brief outline of which follows. The metallic selenium was placed in a platinum strip, bent in the form of a V-trough and supported at the ends by electrodes. The nitrocellulose film was then placed near the strip, and usually floated, together with its brass frame, on a pool of mercury since it was found that more uniform and satisfactory layers could be obtained if a smooth backing of high heat capacity was provided. The whole was then placed in a bell jar, evacuated to the desired pressure (usually *ca.* 1 mm), and the platinum strip heated electrically until the Se began to boil and the whole jar was filled with the fine red powder. Fig. 4 shows the transmission curves for a set of these filters distilled at pressures between 0.03 and 4 mm. It may be seen that the breaks are even

[5] A. H. Pfund, J. O. S. A. **23**, 375 (1933).

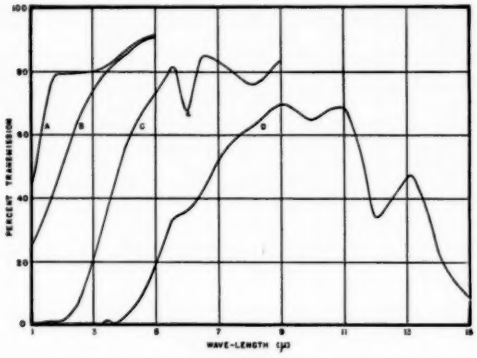



FIG. 3. Transmission of MgO powder filters prepared by holding the nitrocellulose film at varying distances above the magnesium flame. The distances are (*A*) 12 inches, (*B*) 6 inches, (*C*) 3 inches, and (*D*) in the flame. The small dips in the curves are due in part to the true absorption of nitrocellulose (compare Fig. 9).

sharper than those of MgO powder, and that the upper limit of the opacity may be extended well beyond the desired limit of 5.5$\mu$. Filters of this type should, then, be suitable not only for near infrared echelette grating work, but also as filters to remove the short wave-lengths when working in the far infrared. A necessary note of caution is that if these selenium powder filters are warmed to a temperature much above room temperature the particles tend to coalesce and the transmission properties of the filter change markedly, the lower transmission limit moving to longer wave-lengths.

In testing the completeness of the filtering obtained with these powders, two types of test were made. First, points were taken to determine the amount of real energy coming through at wave-lengths less than 5.5$\mu$ and also to determine the amount of ordered energy appearing in the near infrared beyond this point. Secondly, observations were made beyond 40$\mu$ to determine what fraction of the energy there appearing was real and what fraction consisted of orders of the short wave energy. This could be done by comparing deflections taken when the light path was interrupted with a completely opaque shutter, and when a semitransparent shutter of rocksalt was used. The rocksalt plate used was about 1 mm thick, and according to the measurements of Czerny[6] should be quite transparent for wave-lengths shorter than about 30$\mu$ but completely opaque beyond 35$\mu$. If, then, the radiation traversing the exit slit with the spectrometer in position for 45$\mu$ is impure, the radiometer deflection using the opaque shutter will correspond to the total amount of energy in the beam, while that with the rocksalt shutter will correspond only to the total amount of real 45$\mu$ energy present. The energy of shorter wave-length will strike the radiometer whether the shutter is open or closed, and will only cause a shift in the zero position (except, of course, for the small percentage of this energy reflected at the salt air interfaces).

Tests of the above nature were first made with one filter, of Se distilled onto nitrocellulose at 4 mm pressure, and it was found that although, according to the prism instrument measurements, 0.1 percent or less of the short wave energy was transmitted by the filter, even this small amount was enough to give appreciable contributions of impurity to the longer wave-lengths. This serves to exemplify the great care that must be used in devising filters for use in the far infrared. The radiation from a Welsbach mantle, selective though it is, is approximately $10^5$ times as strong at 3$\mu$ than it is at 100$\mu$, so that the thirtieth order of 3$\mu$ radiation, even though reduced in intensity by a factor of 900, can still be important. It was found, however, that two of these selenium filters in series were capable of yielding a quite pure energy spectrum from 40$\mu$ out to nearly 130$\mu$, at which point the third order of the peak near 50$\mu$ began to be

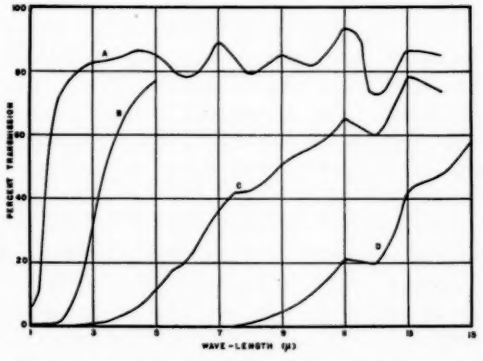



FIG. 4. Transmission of selenium powder filters on nitrocellulose prepared by distilling selenium at different pressures. The pressures are (*A*) 0.03 mm, (*B*) 0.4 mm, (*C*) 2 mm and (*D*) 4 mm.

[6] M. Czerny, Zeits. f. Physik **65**, 600 (1930).

troublesome. In Fig. 5 is shown the final pure energy spectrum obtained.

This method, involving the use of only two easily constructed filters is quite an advance over previous systems, usually involving complicated reflections, and empirically concocted sets of soot, paraffin, etc., filters. It has the additional advantage that, as will be shown later, these selenium filters, after being quite opaque in the regions where this is necessary, increase to quite high transmission values and reduce the efficiency of the apparatus by a minimum amount.

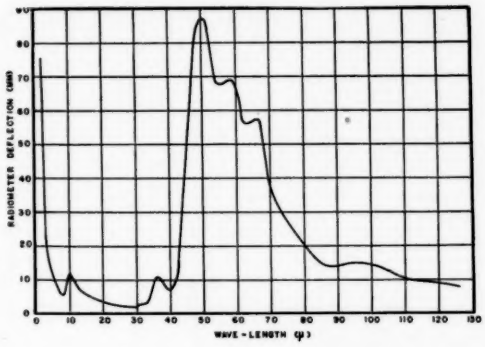



FIG. 5. The final pure energy spectrum obtained by the use of two selenium powder filters. The large deflections below $3\mu$ are due to the fact that the wide slits used in this experiment included a part of the central image.

## SOURCES

Another method whereby the characteristics of the energy spectrum may be regulated is, of course, in the choice and method of operation of the source of radiation. In the previous experiments the source used consisted of a strip some 5–10 mm wide of Welsbach mantle material supported on a brass frame and ignited by a narrow "pin point" flame of illuminating gas. The bright portion of the mantle was usually 2–3 mm wide and 2 cm high, and yielded an image on the first slit not much larger than the slit itself. As the previous curves showed, the troublesome part of the emission from this source consisted largely of the $H_2O$ and $CO_2$ emission bands resulting from the gas flame. If, then, the mantle were heated with a flame of pure hydrogen, the $CO_2$ peak would disappear and a part of the difficulties would be removed thereby. Experiments were made, using this flame, and curves comparing the spectra of the two sources obtained. Actually, the simplification of the filtering problem was not sufficient to make up for the additional difficulties of burning hydrogen, since it was found necessary to use practically the same filter system in either case.

It was also found that a large increase in apparent energy in the long wave region was obtained if the flame was tilted against the mantle in such a way that combustion was incomplete and carbon was deposited. However, when a proper filtering system was used it was found that this effect was spurious, since the increase was really in the short wave region as a result of the increased black-body emission from the glowing carbon on the mantle, and there was no real increase in long wave energy. Fig. 6 shows the true emission curves for the Welsbach mantle source, as determined on the rocksalt prism instrument, for the three types of excitation mentioned above. This black-body radiation from the carbonized Welsbach mantle has a possible application, however. Pfund[7] has recently shown that the Welsbach mantle can be used as a source in the near infrared if it is excited electrically, but according to these experiments, the same effect may be obtained much more simply by merely tilting the flame forward until deposition of carbon on the mantle begins.

The mercury discharge in quartz, which has been recommended as a selective source for certain regions of the spectrum, was also investigated. It was found, though, that the filtering problem in connection with this source was much more difficult since, as a result of the heating of the quartz tube there was a large amount of short wave-length black-body radiation. The selectivity was actually much poorer than that of the Welsbach mantle, which is comparatively free of the troublesome short wave-length radiations.

## TRANSMISSION CURVES

In this section are given transmission curves for a number of substances, most of which have been of interest in connection with the filtering problem. These curves were all taken using two

[7] A. H. Pfund, Science **82**, 597 (1935).

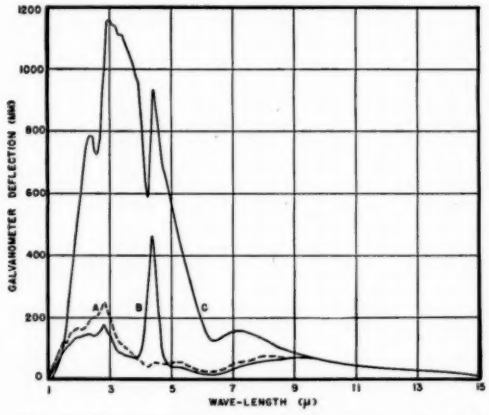



FIG. 6. Prism spectrometer emission spectra of a Welsbach mantle with three different types of excitation. (*A*) hydrogen flame, (*B*) gas flame, (*C*) carbon-depositing gas flame.

selenium powder filters in the instrument, a Welsbach mantle source, and with a slit width of usually two to four mm, so that the resolution is low. In Fig. 7 are shown curves for powdered MgO, selenium and quartz, and for camphor soot all on nitrocellulose films and also for a clear nitrocellulose film. These curves show why quartz powder was found unsuitable as a filtering material, and also why either MgO or selenium would be quite desirable due to their high transmissions. Camphor soot has been quite widely used in the past as a filter, but these curves show that a layer of soot thick enough to really cut out the short wave-length energy has a comparatively low transmission in the far infrared. Fig. 8 shows transmission curves for pure paraffin, and for several crystalline powders which have been melted into the surface of the paraffin plate. The powders used in these experiments were for the most part of average diameter 10–20$\mu$, prepared by the airblast method,[4] and were in thicknesses of the order of a few mg per cm$^2$. In NaCl and KCl the fundamental absorptions, at 61 and 74$\mu$, respectively, show up quite clearly. It is believed that since the transmission of NaCl goes up quite sharply after passing through the fundamental, a layer of this powder on a paraffin plate might make a suitable filter for cutting out the 50$\mu$ energy peak, the orders of which become important at about 130$\mu$, and make it possible to extend measurements considerably beyond this point without great loss in efficiency.

In conclusion we have inserted a few curves, run in the region 1–15$\mu$ on the rocksalt prism instrument, on materials of general interest to

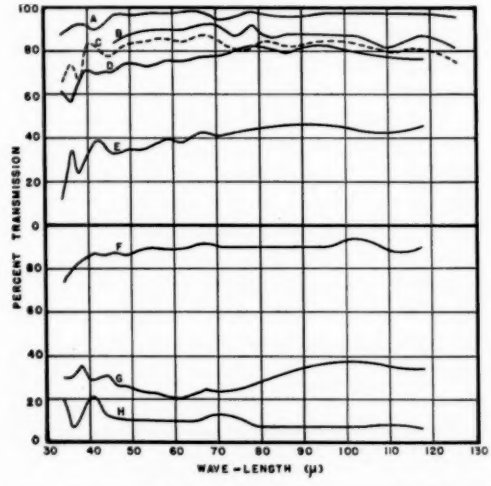



FIG. 7. Transmission curves for several substances mounted on nitrocellulose films. (*A*) clear nitrocellulose, (*B*) selenium powder, (*C*) MgO powder, (*D*) camphor soot, (*E*) very thick layer of camphor soot, (*F*) 1–2$\mu$ quartz particles, (*G*) 50–60$\mu$ quartz particles, (*H*) 100–120$\mu$ quartz particles.

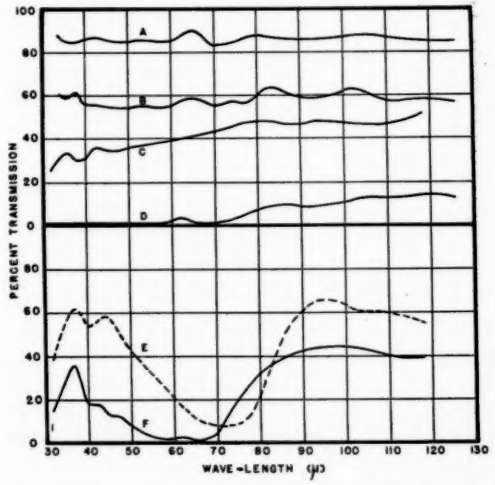



FIG. 8. Transmission of pure paraffin and of several powders melted into the surface of 0.5 mm paraffin plates. (*A*) 0.5 mm paraffin plate, (*B*) 2 mm paraffin plate, (*C*) MgO powder, (*D*) LiF powder, (*E*) KCl powder, (*F*) NaCl powder.

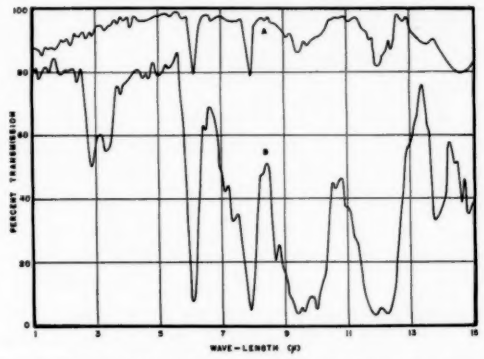



FIG. 9. Transmission of nitrocellulose. (*A*) film of ordinary thickness (0.5–1$\mu$), (*B*) thick film (15$\mu$).

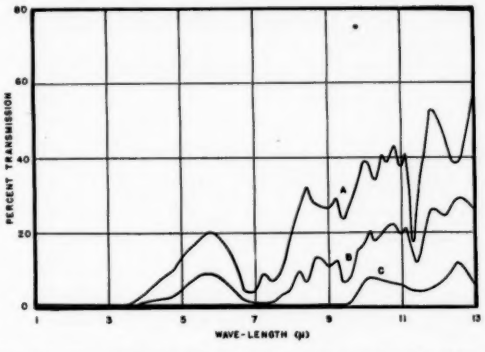



FIG. 11. Transmission of paraffin (melting point 68–72°C). (*A*) 0.6 mm, (*B*) 1.2 mm, (*C*) 2.1 mm.

the experimental spectroscopist. Fig. 9 shows the transmission curves for two thicknesses of nitrocellulose, one thickness (15$\mu$) to bring out the bands clearly, and the other more nearly the size of the film ordinarily used (0.5–1$\mu$). In Fig. 10 are shown rough curves (points at 0.5$\mu$ intervals) on three thicknesses of camphor soot, prepared by holding nitrocellulose films in the smoke from burning camphor for varying periods of time, and of a thin layer of aluminum black prepared by evaporating Al onto nitrocellulose at a pressure of a few mm. Fig. 11 gives the transmissions of three thicknesses of high melting point paraffin (m.p. 68–72°C).

Since there have appeared quite recently two papers on the polarizing properties in the infrared and ultraviolet of the new type of polarizing screen,[8] we include in this article a pair of curves extending these measurements to the transmission limit of the screen. Fig. 12 shows the transmission beyond 1$\mu$ of a pair of "Polaroid" plates, parallel and crossed. It may be seen that the two curves are almost identical and that the polarizing properties in this spectral region are negligible. The opacity of these plates beyond 2.5$\mu$ is due in all probability to the glass on which they are mounted, and has nothing to do with the properties of the material.

We wish to thank Mr. R. R. Brattain and Mr. W. T. Harris for their valuable assistance in preparing the filters and in making the measurements.

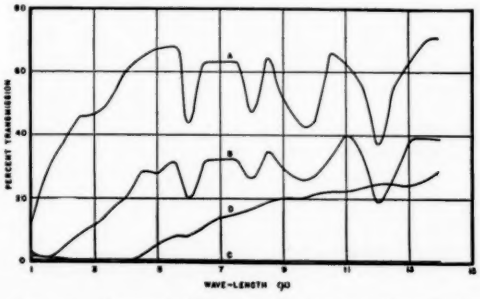



FIG. 10. Transmission of materials on nitrocellulose films. (*A*), (*B*) and (*C*) three thicknesses of camphor soot, (*D*) aluminum black.

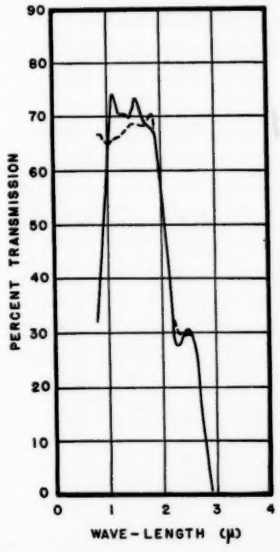



FIG. 12. Transmission of two Polaroid plates, dotted curve parallel and full curve crossed.

[8] L. R. Ingersoll, J. G. Winans and E. H. Krause, J. O. S. A. **26**, 233 (1936); J. Strong, J. O. S. A. **26**, 256 (1936).

# Transmissions of Powder Films to the Infrared Spectrum

JESSE H. PLUMMER, *Johns Hopkins University, Baltimore, Maryland*

(Received June 20, 1936)

SINCE modern analysis of molecular structure requires the highest resolving power in infrared measurements an investigator is almost forced to use echelette gratings. These however, suffer from the defect that the higher orders of lower wave-lengths are reflected with almost full intensity. For any accurate work to be done the effect of these disturbing frequencies must be eliminated to such a degree that their intensity is considerably less than the intensity of the radiation to be measured. Of the methods so far in use, the monochromator as developed by Sleator[1] is not applicable beyond 30$\mu$. Rubens and Aschkinasse[2] have used residual rays with great success below 100$\mu$ but beyond this point the reflection maxima are so broad that second-order effects become serious. Gorton[3] has reflected radiation from rough surfaces but it was found that there was too great an interval between the regions of high and low reflection. Coblentz[4] has investigated the transmission of a large number of substances, but in spite of this there have been too few substances investigated to cover the whole of the infrared with true absorption filters. Pfund[5] and Hardy and Silverman[6] have examined the use of powders as filters but their application has been confined to the spectrum below 9.4$\mu$.

The purpose of the present investigation was to extend this use of powders to see if the method could be applied to the entire infrared spectrum. The success of these powders seemed to offer the only hope of finding filters which could be used beyond 130$\mu$.

The best example of the performance of this type of filter is shown in Fig. 1, which is reproduced from a paper published by Pfund.[5] The average particle size as determined by the count method was 0.088$\mu$. When this filter was examined with transmitted radiation of 0.6$\mu$ and below the percentage transmission was very slight. Presumably, for radiation having a wave-length of less than 0.4$\mu$ it would be virtually opaque. Yet, for radiation of 0.8$\mu$ the transmission was over 50 percent and it transmitted over 90 percent of the 1.6$\mu$ radiation. Apparently for the shorter wave-lengths the particles were sufficiently large to act as small mirrors which vigorously reflected the incident radiation in all directions. Thus the radiation which did get through was so weakened that it was practically negligible. For the longer wave-lengths the particles were small compared to the wave-length and the only loss in intensity was due to the effect of Rayleigh scattering.

Between these two wave-lengths there occurs a region of transition between diffuse reflection and scattering. The exact point at which this transition begins to take place and the slope of the curve in this region depends upon the particle size, the uniformity of the particle size, the uniformity of the layer and upon the thickness of the film.

As the density of the particles was not determined no test could be made of the Rayleigh scattering formula.[7] This expression is:

$$I = I_0 \exp\left(4^2(n^2-n_0^2)^2/(n^2+2n_0^2)^2 N V^2/\lambda^4\right),$$

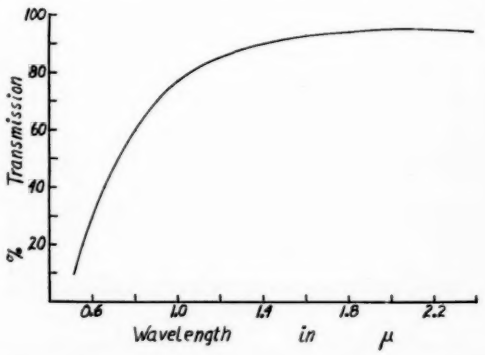



FIG. 1. The transmission curve of a typical powder filter.

[1] Sleator, Astrophys. J. **48**, 127 (1918).
[2] Rubens and Aschkinasse, Ver. D. phys. Ges. **17**, 42 (1898).
[3] Gorton, Phys. Rev. **7**, 66 (1916).
[4] Coblentz, *Supplementary Investigations of Infrared Spectra 5–7* (Carnegie Institute of Washington, 1908).
[5] Pfund, J. O. S. A. **24**, 143 (1934).
[6] Hardy and Silverman, Phys. Rev. **37**, 176 (1931).
[7] Gans, *Wien-Harms Handbuch der Experimental Physik*, Vol. 19, p. 368.

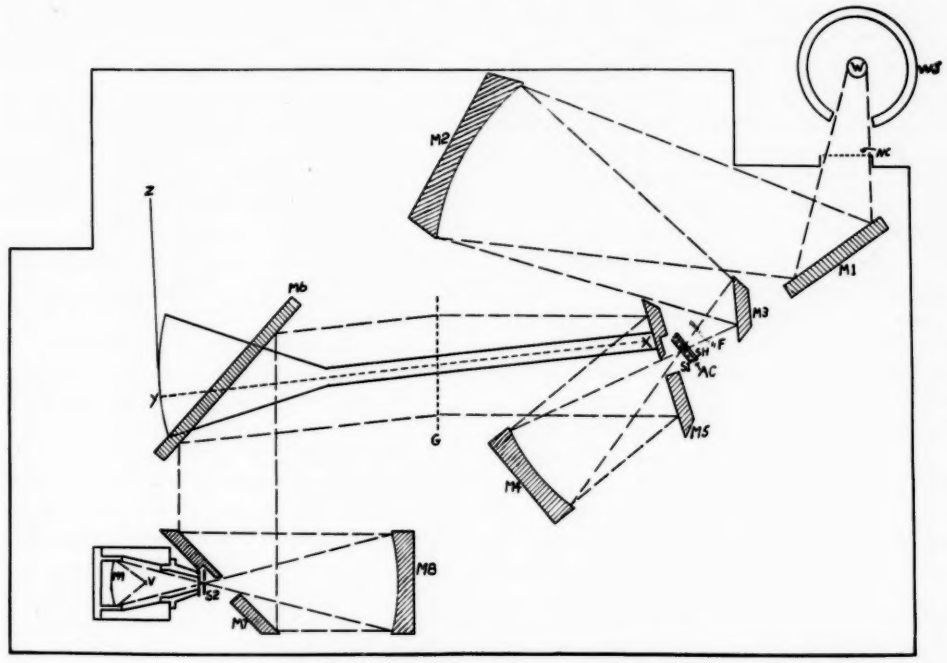



FIG. 2. Arrangement of spectrometer.

| | | | | | |
|---|---|---|---|---|---|
| *W* | —Welsbach mantle | *M*4, *M*8 | —Concave mirrors *F* : 2, 10 cm diameter | *G* | —Position of grating |
| *W*3 | —Water jacket | *M*2, *M*9 | —Concave mirrors | *Y* | —Arc cut with *X* as a center |
| *WC* | —Nitrocellulose film | *M*6 | —Plane mirror rotating about point *X* | *Z* | —Wire leading to micrometer screw to rotate mirror *M*6 |
| *M*1, *M*3 | —Plane mirrors | *S*1, *S*2 | —Slits | | |
| *M*5, *M*7 | —Plane perforated mirrors | *Sh* | —NaCl shutter | *V* | —Position of radiometer vane |
| | | *AC* | —Position of filters | *F* | —Position of test filters. |

where:

$I$ = intensity of transmitted radiation
$I_0$ = intensity of incident radiation
$n$ = refractive index of particle
$n_0$ = refractive index of medium
$N$ = number of particles per cc
$V$ = volume of particle
$\lambda$ = wave-length

However, this law has been tested in the short infrared by Pfund[5] and although the transmission of one filter agreed well with the theoretical result some serious discrepancies were noted.

These were due to the variation in particle sizes. In the tests referred to this variation was deliberately created, but in practice it has not been found practical to obtain spherical particles of a uniform diameter and of such a size as to be suitable for these filters.

In the deduction of the Rayleigh law it was assumed that the particle size was small in comparison with the wave-length. The best of the samples of powders which have been examined in this laboratory contained particles which were sufficiently large as to render the Rayleigh formula inapplicable throughout the region of transition between opacity and transparency. Consequently until some better method is found for the preparation of powders or until the law is modified to take into account the particle size distribution curves for a given sample, agreement between experimental and theoretical results must be regarded as fortuitous.

The transmission of this type of filter in the spectrum from 0.5$\mu$ to 25$\mu$ was measured with the swinging arm spectrometer developed by Pfund[8] in which a potassium bromide prism and a vacuum thermopile with two junctions were employed. For the work between 40$\mu$ and 120$\mu$ wire gratings were used in an $F$ : 2 spectrometer which consisted of the adaptation of the swinging arm principle to the anastigmatic spectrometer. The essential features of these instruments have been published previously so only a diagram will be given of the present apparatus (see Fig. 2).

[8] Pfund, J. O. S. A. **22**, 281 (1932).

A Welsbach mantle was used as the source of radiation. To eliminate the shorter wave-lengths the filters used were a soot film, 1 mm of paraffin, the use of a thin NaCl shutter, 0.7 mm of crystalline quartz (the window of the radiometer case), and the use of a selective radiometer. With these less than two percent contamination was found at any point of the spectrum. For work beyond 80$\mu$ a quartz powder film was added.

With the exception of the Welsbach mantle the entire apparatus was surrounded by a sealed case, the interior of which was dried with $P_2O_5$. This resulted in about 2.5 times greater deflections than those which had been obtained without drying.

The method of winding the grating is shown in Fig. 3. Much better gratings have been obtained this way than by winding two wires side by side and then removing one. Two such frames were clamped in an extensible holder and rotated, the wires being made to fall into the screws *S*. After all of the wires were on, the frame was stretched until the wires were almost at the breaking point. They were then soldered to the bars *B*.

The construction of the radiometer vanes is shown in Fig. 4 where 1 is the front coating of potassium bromide. The dotted layers are made of Japanese lens paper and layers 3 and 9 are of gold leaf. The leaf is used to prevent the escape of radiation to the back surface and to give this surface a high accommodation coefficient. The various parts were first glued together with a sugar solution and then dried. The sheet was then heated between plates until the paper was thoroughly charred. Then the KBr was distilled on the surface in the form of a very fine powder and vanes of the proper size cut from this sheet.

Deflections of the radiometer were measured by means of an optical lever with a scale distance of five meters. In order to secure a stability of one-tenth of a millimeter with this scale distance, it was necessary to mount the radiometer case on a table suspension using the oil tank damping scheme described by Mueller.[9] The radiometer was focused by observing the position of the slit $S_2$ upon the vane. Since the vanes were coated with a white powder the image was easily visible.

The energy curves that were obtained with this spectrometer are shown in Fig. 5. No correction has been made for irrationality of dispersion. The sensitivity indicated in the region from 40$\mu$ to 80$\mu$ is less than it was possible to obtain. Radiometer vanes coated with NaCl gave deflections approximately twice as great as those given by vanes coated with KBr. However, the KBr coated vanes were used to avoid changing radiometers in the course of taking measurements. The gratings used in these experiments had a spacing of 0.8 mm, and the width of the slits was one millimeter. This corresponded to an effective slit width of 4 microns at 80$\mu$.

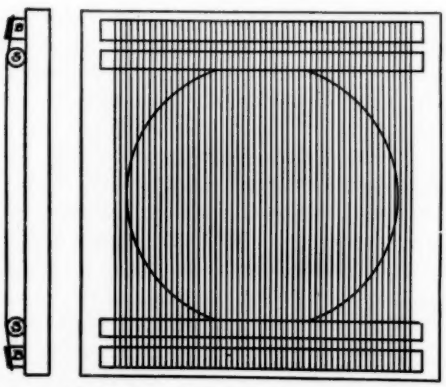



FIG. 3. Method of winding grating. *B*, bars to which grating wires were soldered; *S*, screws to provide accurate spacing of wires.

## METHODS OF FABRICATING THE POWDER FILMS

There are three methods of obtaining the desired powders. They may be evaporated, fumed, or settled out from liquids or gases. Of these methods settling is the most convenient way of separating powders into groups having a

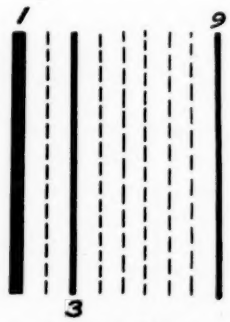



FIG. 4. Construction of radiometer vanes. 1, surface layer of potassium bromide; 3 and 9, gold leaf. The other layers were made of Japanese lens paper.

[9] Mueller, Ann. d. Physik 1, 613 (1929).

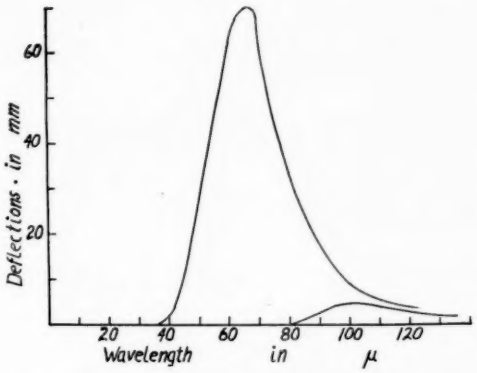



FIG. 5. Energy curves obtained with the spectrometer. The filters used are described in the body of the report. No correction has been applied for the irrationality of dispersion.

uniform particle size. It is not necessary that the filter should be composed of particles of a uniform size, but such a filter will show a much narrower region of transition between the points of zero and maximum transmission than a filter made of a powder with a wide variation in size.

In separating the powders desired from a mixture of all sizes, the procedure is to first remove all of the particles below a given size. This is done by dispersing the mixture in liquid in the ratio of about one part of powder to ten parts of liquid by volume. Then at the expiration of the length of time which would permit the fall of the smallest particle desired from the top of the liquid to within one inch of the bottom of the container, the liquid is siphoned off to this point. Care must be taken so that the liquid below this one-inch level should not be disturbed. This process is repeated until the liquid removed each time is quite clear. The residue or material left in the container now contains only particles of the selected size and greater.

In this way the lower limit of the particle size has been set. To fix the upper limit the residue is again dispersed, and the liquid is siphoned off at the end of the time which will permit the greatest particle desired to fall from the top of the container to within one inch of the bottom. This time the liquid is saved as it contains the desired particles. This process is repeated until all of the different particles have been extracted from the mixture. The residue now contains particles whose lower limit in size has been fixed by the second operation. The above processes may be repeated with it so that any desired groups of powders can be removed from the original mixture.

As an example of the uniformity of the powders that may be prepared in this way, 250 cc of quartz powder which had been passed through a 325 mesh sieve were used for the largest particles. The powder supposedly contained particles of 40$\mu$ diameter and below. After particles of 30$\mu$ diameter and below had been eliminated by means of numerous settlings the remaining one cc was examined under the microscope. Particles were found with sizes varying between 23$\mu$ and 67$\mu$. This is the largest size that must be isolated by sedimentation. Sieves are available for use in obtaining groups of the larger sizes.

In all of the groups measured this was the only one in which the size as determined microscopically fell within the limits determined from the rate of fall. This was usually due to incomplete dispersion and the lack of uniformity in the shape of the individual particles. One percent of sodium metasilicate added to the liquid will help to disperse the quartz particles. The NaCl and KBr particles were ground at a temperature above 100°C and worked into a rough paste with polymerized linseed oil. Kerosene was added gradually until sufficient had been added to start the sedimentation. The continual addition of the kerosene each time that the residue is dispersed implies that only a small fraction of the oil will be found in any given sample. After the particles have once been dispersed no more of the agent is required. Stirring only is necessary to break up the cake in the bottom of the container. If desired the powder may be washed as many times as necessary to remove all traces of the dispersing agent.

The quartz powders when separated were dispersed in small quantities of water and poured out on a level nitrocellulose film and either heated or allowed to stand over the week end to dry. Beautifully uniform films may be made in this way. The thickness may be varied by using different amounts of powder. If the areas required are small the films may be tilted slightly and a wedge shape layer of powder deposited. This method was not used in the case of the NaCl or KBr powders. As kerosene destroyed the

nitrocellulose these particles were deposited on either gold mirrors or upon thin plates of NaCl.

The curves in Fig. 6 illustrate the performance of these powder filters. They also indicate that this use of powders may be applied to the majority of the infrared spectrum. The quartz powder of $37\mu$ average particle size should serve quite adequately as a filter to eliminate wave-lengths below $60\mu$. These quartz films all transmit between $7\mu$ and $8\mu$ as shown. This is an entirely different effect and has been pointed out elsewhere by Pfund.[10]

Since the energy is so low in the far infrared, it will probably prove best to depend upon the combined use of crystalline quartz, paraffin, MgO, soot and the use of a selective shutter to eliminate the wave-lengths below $40\mu$ and depend upon the large quartz powder to eliminate the band from $40\mu$ to $80\mu$. This will allow much thinner layers of powder to be used with the resulting higher transmissions and higher energies in this region. All of the other substances mentioned above have been found by Barnes[11] to be highly transparent beyond $40\mu$. Magnesium oxide has not been measured previously but in this work it was found that thick layers fumed on nitrocellulose films absorbed less than ten percent of the incident radiation.

In the shorter wave-lengths quartz powders make an almost perfect filter for the region between $6.5\mu$ and $7.9\mu$, their only defect is that the transmission is not more than about 40 percent.

In the region between $0.5\mu$ and $10\mu$ the most practical filters may be made by fuming MgO on nitrocellulose or by distilling selenium under suitable conditions on the same kind of film. Details of the method of distillation have been published by Pfund.[5]

Powders obtained by settling are applicable in the region between $10\mu$ and $40\mu$. It is not practical to make them for the shorter wave-lengths as it takes far too much time to separate the particles. NaCl and KBr are suitable for this part or the spectrum. These materials may be used somewhat beyond the point where they are generally recognised to be opaque. This is due to the fact that the films are usually much thinner than any samples that are ordinarily used.

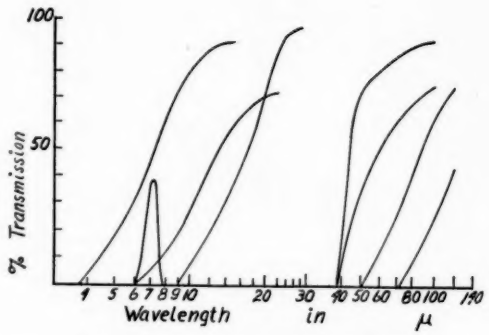



FIG. 6. Transmissions of powder filters.

| FILTER No. | MATERIAL | PARTICLE SIZE IN AS DETERMINED MICROSCOPICALLY | PARTICLE SIZE IN AS DETERMINED FROM STOKES' LAW |
|---|---|---|---|
| 1 | NaCl | 1.8 | 2–4 |
| 2 | KBr | 3.2 | 5–7 |
| 3 | KBr | 3.6 | 6–8 |
| 4 | $SiO_2$ | 10.6 | 15–20 |
| 5 | $SiO_2$ | 20.1 | 25–30 |
| 6 | $SiO_2$ | 28 | 25–35 |
| 7 | $SiO_2$ | 37 | 30–40 |

One other point should be mentioned. That is, the reflection type filter, in which the powder is deposited upon a mirror, is not nearly so efficient as the filters made by depositing the powder on a transparent material. The reason for this is that a small part of the diffusely reflected radiation will be mixed with the radiation which has passed through the film and been reflected back. This contamination may be of the order of 0.1 percent but 0.1 percent of the $3\mu$ radiation is a large amount compared with the energy at $12\mu$.

To give specific directions for making a powder filter to eliminate the wave-lengths below any desired point is difficult. The powders should be obtained from a substance which is highly transparent over the region and they should be obtained in groups whose average particle size varies between one-half and one-eighth of the wave-length at which the transition is desired to begin. From here on it is a matter of trial and error to determine the best thickness and particle size to fit individual needs. A few trials should suffice to give a filter of the desired characteristics.

In conclusion the author wishes to express his appreciation to Professor A. H. Pfund and Dr. J. A. Bearden for their many kind suggestions.

[10] Pfund, J. O. S. A. **23**, 375 (1933).
[11] Barnes, Phys. Rev. **39**, 562 (1932).

# The Electric Welsbach Lamp

A. H. PFUND, *Rowland Hall, Johns Hopkins University, Baltimore, Maryland*

(Received October 19, 1936)

This lamp is to serve as a source of radiation from the visible into the far infrared. The heating unit consists of sheets of ashed Welsbach mantle heated by the glow or arc discharge formed between terminals connected to the secondary of a high potential transformer. When operated in air, a small, pointed gas flame is allowed to play on the mantle, thus steadying the electrical discharge and increasing the temperature. From 0.7 to 15$\mu$, gas plus electricity are used, whereas, from 15$\mu$ to 150$\mu$, gas alone is employed. When the lamp is operated in a partial vacuum, variations in spectral distribution are effected largely by working at different pressures. At pressures around 10 cm the emission is similar to that of the gas Welsbach in the region of longer wave-lengths, while at pressures near 30 cm the emission rivals that of a Nernst lamp in the near infrared (0.7 to 15$\mu$).

AFTER Rubens[1] had demonstrated that the emissive power of the gas heated Welsbach mantle is low in the near infrared but approaches unity in the region of greater wave-lengths, this source has been used widely for the study of the far infrared. With the hope of developing the mantle as a universal source for the entire infrared, it was proposed tc increase the emission in the near infrared by operating at temperatures higher than those obtainable with the Bunsen flame. This appeared entirely feasible since the mantle contains more than 99 percent thorium oxide whose melting point is greater than 2800°C. Preliminary experiments with the oxyhydrogen flame were but moderately successful. The mode of heating finally adopted involves the introduction of the mantle[2] into the arc discharge between terminals connected to the secondary of a high potential transformer. Because of the flexibility of this procedure it is possible to realize in the same source one which rivals, successively, the performance of the Nernst lamp in the near infrared (0.7$\mu$ to 15$\mu$) and that of the gas Welsbach in the far infrared (15$\mu$ to 150$\mu$).

It has been found that the electric Welsbach may be operated either in the open air or in a partial vacuum. The design of the lamp operating in the open air is shown in Fig. 1 where *AA* is a pair of copper electrodes (4 mm thick), mounted between two square disks of asbestos board *BB* which are about 5 mm thick and 6 cm on an edge. Central openings about 15 mm in diameter allow radiation to escape. The inner portion of each electrode is cut down to half-thickness at *SS* and the projecting knobs are drilled centrally so as to receive pieces of platinum wire *KK* (0.7 mm in diameter) held in place by friction and separated by about 13 mm. These wires, which project by 3–4 mm are later heated by the discharge so that a small bead is formed at each end. Since the discharge takes place between these incandescent beads the intensity of the emitted radiations becomes very constant. To introduce the mantle, the system is unbolted, rectangular pieces are cut out of a commercial mantle;[3] two or three pieces $W_2$ are placed on one of the asbestos disks and are ashed with a small pointed gas flame; next, the copper electrodes are

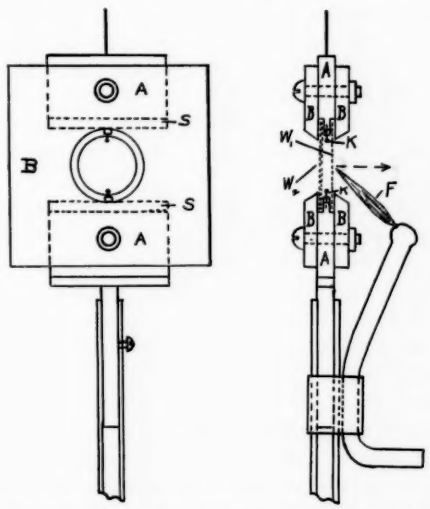



FIG. 1. Showing front and side views of lamp to be operated in air. Heating of mantle *W* is effected by gas flame *F* alone for long heat waves and by gas plus electricity for visible and near infrared radiations.

[1] H. Rubens, Ann. d. Physik **18**, 725 (1905).
[2] A. H. Pfund, Science **82**, 597 (1935).
[3] Reflex Gas Mantle No. 107, manufactured by the Welsbach Company.

put in place and a single layer of mantle $W_1$ is laid on the electrodes and is, likewise, ashed. After the upper asbestos disk has been put in place and the bolts have been inserted, the assembly is complete. It is important that the pieces of mantle be quite free, i.e., not clamped, since contractions and distortions produced by heating will otherwise tear the mantle.

The copper electrodes are connected to the secondary of a transformer rated at about 10,000 volts and the current is controlled by suitable resistance in the primary circuit. The current passing through the lamp may be varied from 10–50 ma; the potential drop is of the order of 1000 volts. To increase the temperature of the mantle above that produced by the electrical discharge, a small gas flame $F$ about 3 cm long is allowed to play on the mantle $W_1$. Not only is the intensity of the radiation in the near infrared enhanced, but the steadiness of operation is improved. That the current is carried by the mass of gas between the electrodes and not by the mantle is proved by the observation that even though the mantle be torn squarely across the line of discharge, the intensity of the emitted radiation is not affected. The lamp functions best when the flame is so adjusted that the discharge is virtually noiseless. The constancy of the emitted radiation is determined almost entirely by the constancy of the alternating voltage supply. As will be shown by later tests, the lamp is to be heated by electricity and gas for the visible and near infrared and by gas alone for the far infrared.

The construction of the lamp to be operated in a partial vacuum is shown in Fig. 2. The heater element remains essentially unaltered, dimensions alone being modified to make possible the insertion into a glass tube. Since the various parts are lettered as on Fig. 1, repetition of a detailed description becomes superfluous. The glass tube $G$ is of Pyrex and has an internal diameter of 3 cm and a length of 15–20 cm. The side tubes are supplied with brass water jackets $ZZ$ whose ends are closed, respectively, with polished plates of rocksalt $R$ and crystalline quartz $Q$. Since the quartz plate was but 0.3 mm thick, it would not withstand atmospheric pressure over a clear opening 2.5 cm in diameter. The construction adopted to overcome this difficulty (Fig. 2) consists of a brass plate $L$ with a circular opening 25 mm in diameter. Six radial fins are sweated into the brass disk and one pair of fins $FF$, filed thin in the middle, stretches across the opening. These fins are filed flush with the top of the brass plate and all edges which are to come into contact with the quartz plate are slightly rounded. The quartz plate is attached firmly with sealing wax and the assembly is then attached to the water jackets with a mixture of beeswax and rosin. Trial has shown that the obstruction of radiation by the fins is less than 10 percent.

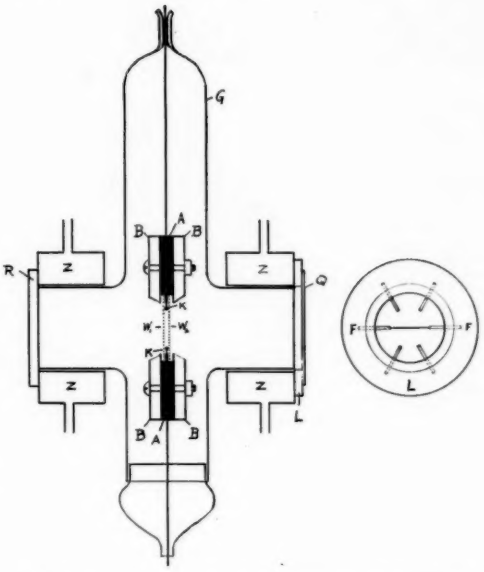



FIG. 2. Showing side-view of lamp to be operated in partial vacuum. The mantle $W$ is heated by the electrical discharge between platinum beads $K$.

At an electrode separation of 12–15 mm the arc will not strike at atmospheric pressure. However, at a pressure of 25 cm or less, the discharge sets in. At pressures between 5 and 10 cm and with a current of 20 ma the mantle glows with a pale yellowish-green light. At a pressure near 10 cm the radiation is identical with that of the gas-heated mantle the $CO_2$ bands of emission being, of course, absent. At pressures of 40 cm the mantle rivals the gas-filled tungsten lamp in brilliancy. In the pressure range 5–40 cm the current through the lamp remains constant. The brightness of the lamp

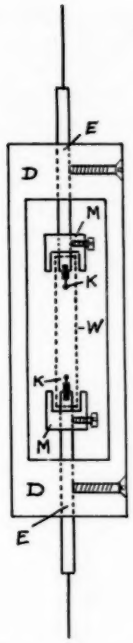



FIG. 3. Showing design of lamp adapted for use of radiating materials in cylindrical form.

may therefore be increased both by raising the pressure and increasing the current.

A further modification for the heating of materials in cylindrical form is shown in Fig. 3. Here a frame *DD* of asbestos board (sheet-rock) holds the electrodes *EE*. These are supplied with cups *MM* which serve to hold the heater *W* in place. The heater consists of thin walled tubing of fused quartz or of Welsbach mantle, formed into a cylinder after having been moistened. With Welsbach material the lamp functions well at atmospheric pressure, but with the quartz tubing a partial vacuum appears to be necessary.

Since the lamp burning in the open air (Fig. 1) is the most serviceable, tests on this type of lamp alone will be discussed. Spectral distributions were studied with a rocksalt sepctrometer supplied with a single junction thermopile, sensitized with $CCl_4$ vapor.[4] In Fig. 4 are shown the ratios of the emissions of the lamp under the several modes of excitation relative to those of a Nernst lamp operated at a color temperature

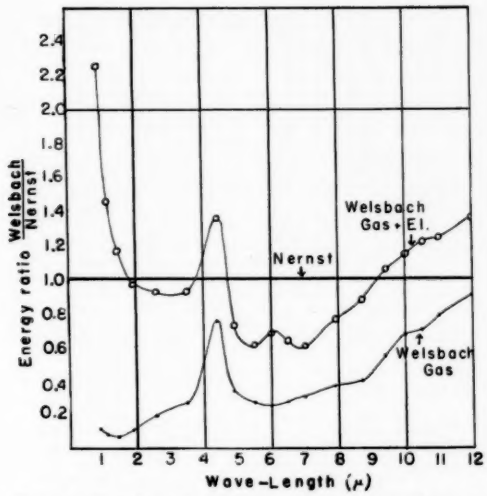



FIG. 4. Showing the emission, relative to that of a Nernst lamp (2240°K), of the gas-heated mantle (lower curve), and of the mantle heated by gas plus electricity (upper curve).

of 2240°K.[5] As might have been anticipated, the emission of the gas-heated mantle while low in the region of the near infrared, approaches that of the Nernst lamp near 12$\mu$. When the heating is effected with gas plus electricity, the relative emission is considerably greater than that of the Nernst near the visible and the region beyond 9$\mu$. To be sure, in the region 5$\mu$ to 7$\mu$ the relative emission drops to 60 percent of that of the Nernst. However, since the total energy is large in this region a moderate falling off is not a serious drawback.

A second series of tests on the emission in the region of long waves (50$\mu$) was carried out. Radiations from the lamp were first reflected from a polished plate of rocksalt, then, from a roughly ground, silvered glass plate and were finally focused on an evacuated thermopile, coated with zinc black[6] and covered with a plate of crystalline quartz 0.3 mm thick. To reduce the intensity of the near infrared two filters of grayish selenium powder[7] distilled at a pressure of 8 mm on sheets of Pliofilm[8] stretched tightly

[4] A. H. Pfund, J. O. S. A. **25**, 351 (1935).

[5] I am indebted to Dr. W. E. Forsythe who calibrated for me a tungsten lamp in terms of color temperatures *vs.* voltage drop through the lamp.

[6] A. H. Pfund, J. O. S. A. **23**, 375 (1933).

[7] A. H. Pfund, J. O. S. A. **23**, 376 (1933).

[8] Pliofilm is chlorinated rubber in sheet form, made by the Goodyear Rubber Company.

over rings of fiber were introduced. A single layer of Pliofilm transmits 76 percent of 50$\mu$ radiation, while a single layer of selenium powder (which transmits less than 1 percent at any wave-length between 0.5$\mu$ and 12$\mu$) allows 86 percent of the long wave radiation to pass. Since a plate of quartz is in the light path it may be assumed that the spectral region between 7$\mu$ and 35$\mu$ is absent. A polished plate of rocksalt 3 mm thick was used as a filter to eliminate radiations in the region beyond 35$\mu$. The resultant galvanometer deflections are shown in the following table:

| Gas heating | Gas plus electricity | | |
|---|---|---|---|
| 105 mm | 240 mm | Rocksalt plate in | metal shutter. |
| 375 mm | 630 mm | Rocksalt plate out | |

As might have been anticipated, these results show that, while the radiations emitted by the mantle heated by gas and electricity are the more intense, the ratio of short wave-length to long wave-length emission is greater than in the case of the gas-heated mantle. Experiments carried out with the lamp operating in partial vacuum (Fig. 2) showed that it is possible to duplicate the ratio of long to short wave-length energies of the gas-heated mantle by operating at a definite mantle temperature.

In conclusion, the writer wishes to express his gratitude to Dr. H. S. Miner, chemist-in-chief of the Welsbach Company, for preparing a special series of mantles with varying ceria-thoria content.

# The Polarimetric Determination of Optical Properties

RICHARD M. EMBERSON, *Physics Laboratory, University of Missouri, Columbia, Missouri.*

(Received October 27, 1936)

An attempt to determine the thicknesses of thin films by the polarimetric method evolved into a study of the method itself. This paper contains a summary of the equations and a description of the experimental technique used in the study, as well as experimental results. It has been found that the optical constants of metals are practically independent of the angle of incidence. Film thicknesses, calculated from polarimetric data, were found to be of the correct order of magnitude but not to be independent of the angle of incidence. Also, the computed thicknesses were always complex.

## THEORY

THERE are available several theoretical treatments of the reflection and refraction of polarized light. Drude's[1] work and the later work of König[2] are perhaps the best known. In the present study, however, the author preferred to use equations published by Fry.[3] Numbered equations, notation, etc., follow Dr. Fry's papers, to which the reader is referred for a complete and lucid discussion of the subject.

The problem of the determination of the optical constants of a surface will be taken up first, since it is an integral part of the problem of the determination of thin film thicknesses. Eq. (55)[4]

$$N+iK_0=\tan I[1-4\rho \sin^2 I/(\rho+1)^2]^{\frac{1}{2}}, \quad (55)$$

gives a relationship between the index of refraction $N$ and the absorption coefficient $K_0$ and observable quantities, the angle of incidence $I$ and $\rho=\tan\theta e^{i\varphi}=E_\perp/E_{||}$. $\varphi$ is the relative phase shift, introduced by the reflection at the surface, between two components of light, one plane-polarized parallel to the plane of incidence and the other polarized perpendicular to the plane of incidence; $\varphi$ is the same as Drude's $\Delta$. $\theta$, which is the complement of Drude's azimuth angle $\psi$, is defined by the equation, $\tan\theta=$amplitude $E_\perp$/amplitude $E_{||}$, for the reflected light. In this equation, it is assumed that the amplitudes of $E_\perp$ and $E_{||}$ were equal before reflection.

The equation which expresses the relationship between the thickness of a thin film, the optical constants of the various media involved, and the observable quantities is much more complicated. The second equation in the group numbered (53) gives the relation between components of light, polarized perpendicular to the plane of incidence, before and after reflection at a film-covered surface. A similar relationship between the components polarized parallel to the plane of incidence may be written in terms of Dr. Fry's $\kappa$'s. If the incident light was such that the two mutually perpendicular plane-polarized components were equal in amplitude and in phase, the ratio of the two reflected components would be related to the observable quantities $\theta$ and $\varphi$ by the equation:

$$\rho=\frac{(k-k_1)(k_1+k_4)X^2+(k+k_1)(k_1-k_4)}{(k+k_1)(k_1+k_4)X^2+(k-k_1)(k_1-k_4)} \cdot \frac{(\kappa+\kappa_1)(\kappa_1+\kappa_4)X^2+(\kappa-\kappa_1)(\kappa_1-\kappa_4)}{(\kappa-\kappa_1)(\kappa_1+\kappa_4)X^2+(\kappa+\kappa_1)(\kappa_1-\kappa_4)}. \quad (A)$$

The $k$'s and $\kappa$'s[5] involve the angle of incidence of the light and the optical constants of the various media to which the subscripts refer. $X$ involves the frequency and angle of incidence of the light as well as the film thickness.

Obviously, Eq. (A) is rather cumbersome. Apparently, Ives and Johnsrud[6] computed film thicknesses by means of such an equation, by assuming various values for the film thickness and then calculating the corresponding values of $\rho$. "Iso-thickness" curves were plotted which

[1] P. Drude, Ann. d. Physik **32**, 584 (1887); **34**, 489 (1888); **36**, 532 (1889); **39**, 481 (1890).

[2] König, *Handbuch der Physik*, Vol. **20**, p. 245 (1928).

[3] T. C. Fry, J. O. S. A. **15**, 137 (1927); **16**, 1 (1928); **22**, 307 (1932).

[4] Confirmed by letter from Dr. Fry. A change in notation while the manuscript was being prepared for publication resulted in an error in the original article.

[5] Fry, reference 3, **16**, 8–9.

[6] H. E. Ives and A. L. Johnsrud, J. O. S. A. **15**, 378 (1927).

showed the theoretical variations of $\theta$ and $\varphi$ with the angle of incidence for the various assumed film thicknesses. Observed values of $\theta$ and $\varphi$ were then plotted. The iso-thickness curve which best fitted the observed values gave the film thickness.

If $X$, in Eq. (A), is expanded into a power series, second and higher order terms in the film thickness may be dropped with errors of less than 2 percent, provided the film thickness is small, i.e., about 100A or less. Define:

$$a=k_1(k-k_4),$$
$$b=iq_1c_1(k-k_1)(k_1+k_4),$$
$$c=k_1(k+k_4),$$
$$d=iq_1c_1(k+k_1)(k_1+k_4),$$

and similarly $\alpha$, $\beta$, $\gamma$ and $\delta$ in terms of the $\kappa$'s.

Then, $$\rho=(a+b\zeta)(\gamma+\delta\zeta)/(c+d\zeta)(\alpha+\beta\zeta), \quad \text{(B)}$$

where $\zeta$ is the film thickness. If $\rho(\zeta)$ is the observed value of $\rho$ for a film of thickness $\zeta$, and $\rho(0)$ is the observed value of $\rho$ for no film, a Maclaurin's series expansion yields:

$$\zeta=[\rho(\zeta)-\rho(0)]\Big/\left[\frac{a\delta+b\gamma}{c\alpha}-\frac{a\gamma(d\alpha+c\beta)}{(c\alpha)^2}\right]. \quad \text{(C)}$$

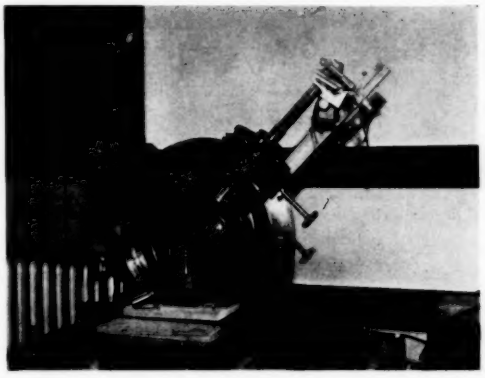
In some cases, e.g., near the Brewster angle on glass, Eq. (C) is not applicable. For these cases, one may form an expansion of $1/\rho(\zeta)$, with the final result:

$$\zeta=\left[\frac{1}{\rho(\zeta)}-\frac{1}{\rho(0)}\right]\Big/\left[\frac{d\alpha+c\beta}{a\gamma}-\frac{c\alpha(a\delta+b\gamma)}{(a\gamma)^2}\right]. \quad \text{(D)}$$

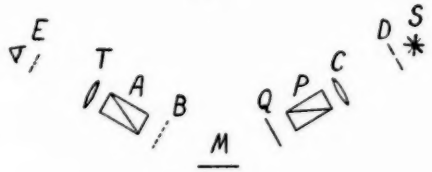
Eqs. (C) and (D) would not only simplify the construction of iso-thickness curves but also permit the computation of film thickness directly.

## Experimental Technique

A Babinet compensator is the most widely used instrument in polarimetric work. More sensitive analyzing systems have been devised.[7] In the present study, after some observations had been taken with a Babinet compensator, a more sensitive instrument was designed and constructed.[8] The optical arrangement most nearly



(a)




(b)

FIG. 1. (a) Photograph of instrument; (b) optical train.

resembles that used by Tronstad and Feachem;[9] following Skinner's[10] suggestion, the instrument might well be called a universal polarimeter. Fig. 1 shows a side view of the instrument and a schematic drawing of the optical train. Light from a suitable source $S$ passes through the collimator $D$–$C$. The resulting bundle of parallel rays passes through a Nicol prism $P$, through a quarter-wave plate $Q$, and is reflected from the mirror surface under examination $M$. The analyzer consists of a telescope with cross hairs and eye-piece $T$–$E$, a Nicol prism $A$, and a biplate $B$, which is removed for certain parts of the work.

The photograph shows the main mechanical features of the instrument. A disk of cold-rolled steel, about twenty-two inches in diameter and one-half inch thick, is mounted on a rigid frame. The polarimeter is shown set up for observation on liquid surfaces. If a short leg is screwed into the back of the disk, the whole instrument may be laid over on its back, in which position it more nearly resembles an ordinary spectrometer. Two slip plates, with cross sections resembling a very

[7] A. Q. Tool, Phys. Rev. **31**, 1 (1910); L. D. Weld, J. O. S. A. **6**, 67 (1922).

[8] The polarimeter was constructed in the instrument shop of the University of Missouri, under the direction of Mr. Gus Tornsjo, the chief technician.

[9] C. G. P. Feacham and Leif Tronstad, Proc. Roy. Soc. **A145**, 115 (1934).

[10] C. A. Skinner, J. O. S. A. **10**, 491 (1925).

flat $E$ with the central prong removed, slide around the outer circumference of the disk, and furnish very solid bases upon which the telescope and collimator arms are mounted. The slip plates are connected to flat ring bearings at the center of the disk and to lead counter weights at the opposite sides. A twelve-inch graduated circle[11] is fastened to the telescope arm, and the alidade is fastened to the collimator arm. The circle is graduated to read to 10″ of arc.

The telescope and collimator arms are practically identical in construction. The circles obtained for these arms are the type used for the horizontal circle of a surveyor's transit. They are graduated to read to 20″ of arc. The quarter-wave plate was made by a method which has been fully described elsewhere.[12] Several methods are described in the literature for making biplates.[13] A biplate is an arrangement of thin pieces of optically active material in which the field is divided, and the direction of the optical axis on one side is perpendicular to the direction of the optical axis on the other side. In addition, the effective thickness must be the same on both sides of the field. Obviously, the simplest method of making a biplate would be to make two straight cuts, one perpendicular to the other, through a thin sheet of mica. Two pieces may then be chosen such that, when they are laid edge to edge, the optical axis in one piece is perpendicular to that of the other, and the thickness of mica is the same on both sides of the field. Several biplates were made by this method. The very thin sheets of mica were cemented between two pieces of strain-free glass. The finished plate is less cumbersome than plates made by some of the other methods. However, it is purely a matter of chance whether or not the directions of the optical axes in the two halves of the field are exactly perpendicular, and a number of attempts must be made before a satisfactory plate is produced.

A support is provided at the center of the instrument disk for a central table, which corresponds to the prism table of a spectrometer. When the instrument is set up for observation on liquids, as shown in the photograph, an auxiliary support is used. This is mounted on a pile of lead blocks which are separated by pieces of sponge rubber. The introduction of light into the collimator is accomplished by the simple procedure of mounting the source on an arm which can be rotated about an axis approximately coinciding with the central axis of rotation of the instrument. The source was a mercury arc with glass filters which transmitted the green line, $\lambda = 5461 \times 10^{-8}$ cm.

The quantities $\theta$ and $\varphi$, which determine the $\rho$ in Eqs. (55) and (A), in general cannot be observed directly with this polarimeter. Let us take the plane of incidence, i.e., the plane parallel to the disk of the instrument, as a reference plane. Then, define $P$ as the angle which the plane of polarization of the light transmitted by the polarizer Nicol makes with the plane of incidence. Similarly, let $Q$ be the angle which the optical axis of the quarter-wave plate makes with the plane of incidence. The positive direction for both these angles is that in which a right-handed screw would be turned to advance it along the incident ray of light. It can be shown, then, that for $Q = \pm 45°$,

$$\begin{aligned} \tan\theta &= \tan A, \\ \tan\varphi &= \pm\tan(2P-90). \end{aligned} \tag{E}$$

$A$ is the azimuth angle of the analyzer Nicol prism when set to extinguish the reflected light. Like $P$ and $Q$, $A$ is also measured from the plane of incidence.

From the more general equations from which Eqs. (E) are obtained, it can be shown that:

$$\begin{aligned} d\theta &= dA - 2\sin A\,[\sin 2P\,dQ \\ &\qquad + \tfrac{1}{4}(\sin 2P + \cos 2P)\,d\delta], \\ d\varphi &= 2dP - 2dQ. \end{aligned} \tag{F}$$

$\delta$ is the phase angle introduced between the ordinary and extraordinary rays of the mica plate; since the plate is supposed to be a quarter-wave plate, $\delta$ is about 90°. The possible errors $d\delta$ and $dQ$ were about constant and of the order of 1′ of arc.

In the use of the polarimeter, angle $P$ is so adjusted that the biplate, when viewed through the analyzer Nicol and telescope with the eye-piece removed, shows the reflected light to be plane polarized. Then, the biplate is removed and

[11] I am indebted to Dr. E. S. Haynes of the Department of Astronomy for this circle.
[12] R. M. Emberson, J. O. S. A. **26**, 63 (1936).
[13] Leif Tronstad, J. Sci. Inst. **11**, 144 (1934); E. Perucca, J. Sci. Inst. **12**, 8 (1935).

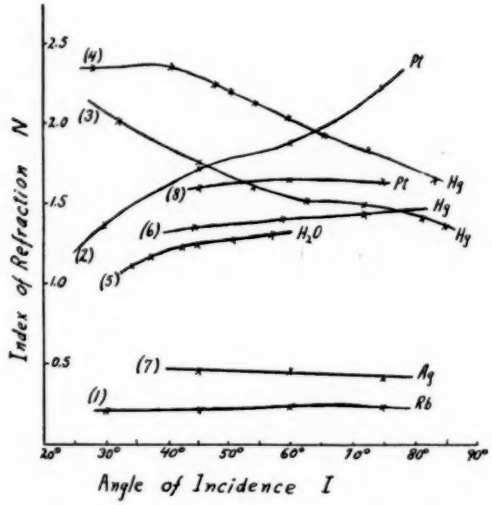



FIG. 2. Change of index of refraction with the angle of incidence. Curves 1 and 2 from Ives' data; curve 3 from data given by Tronstad and Feachem.

the azimuth angle $A$ determined. It should be evident, then, that the size of the possible errors $dA$ and $dP$ would depend on the intensity of the light and, in the case of $dP$, on the biplate. Under the best conditions, the average of several observations might determine $P$ and $A$ to within a minute or so of arc.

A word of caution concerning the biplate: a discussion of the theory of a biplate showed, as was found experimentally, that regardless of the ellipticity of the light which falls on the biplate, there will be some orientation of the biplate and analyzer Nicol prism such that the two halves of the field of the biplate will be of equal brightness.

## DETERMINATION OF OPTICAL CONSTANTS

Drude's equations, for use in computing the optical constants of a material from observed quantities, are somewhat simplified for the special case for which the relative phase shift is exactly 90°. Many workers in this field have utilized these special equations, or the corresponding equations from König's work. If these special equations are used, however, the observations on any one substance must necessarily be made at that certain angle of incidence (Drude called it the angle of principal incidence) for which the relative phase shift due to the reflection is exactly 90°.

In the present study, observations were made over a range of values of the angle of incidence. The results computed from preliminary observations made with both the Babinet compensator and the universal polarimeter indicated that the optical constants varied with the angle of incidence of observation. These results are in accord with a statement by Wood.[14] An investigation showed that of the relatively few people who had made observations at all angles of incidence, most obtained results which indicated a variation of the optical constants with the angle of incidence. The usual procedure, in such cases, is to give most weight to the observations made at the angle of principal incidence. The correctness of this procedure, however, is somewhat doubtful, since a study of Eq. (55) does not verify Drude's conclusion[15] that observational errors have the least effect on the results computed from the observations taken at the angle of principal incidence (Drude's $\Delta$ equal to $\pi/2$, and $\psi$ as small as possible).

In Fig. 2, computed values of the index of refraction $N$ are plotted as ordinates and the corresponding values of the angle of incidence $I$ as abscissae. Curves 1 and 2, for rubidium and platinum, respectively, are plotted from data given by Ives and Johnsrud in their article referred to previously. Curves 3 and 4 are for mercury. Curve 3 is from data given by Tronstad and Feachem; curve 4 is from data obtained by the author, and is the mean of observations made on nine different mercury surfaces.

Table I gives samples of the observed data and computed results. The quantities $I$, $\theta$, $\varphi$, $N$ and $K_0$ have been defined previously.

It will be noticed that curve 4 is convex upward, just the opposite of curve 3. This was rather perplexing, since Tronstad and Feachem took many precautions in their determination of the optical constants of mercury and felt that their determination was probably the most accurate ever made. In an effort to explain this difference, the entire experimental procedure was carefully checked. In the course of this work,

[14] R. W. Wood, *Physical Optics*, third edition (Macmillan, 1934), p. 555.
[15] P. Drude, Ann. d. Physik **39**, 508 (1890).

some observations were made on distilled water, with the results shown by curve 5. For distilled water, only the angles $\theta$ and $I$ enter the computations. Possible sources of error in the determination of $I$ were eliminated, leaving the trouble in the determination of $\theta$. The source of error was found to be in the zero readings of the Nicol prisms.

The method which first occurs to anyone wishing to determine the zero readings of an instrument such as the one under consideration is to reflect light from the surface of water at the Brewster angle of incidence. Since the reflected light is almost completely plane polarized perpendicular to the plane of incidence, if the analyzer Nicol is crossed with this light the zero reading of the telescope circle can be determined.

Since it is much more sensitive, M'Connel's[16] method was used. It has the disadvantage that the zero reading of the Nicol prism is obtained with reference to the axis of rotation of the table which supports the auxiliary Nicol needed for this method. Obviously, if this axis of rotation is not accurately perpendicular (or parallel) to the plane of incidence, the angular positions of the Nicol prisms, which are supposed to be measured from the plane of incidence, will all be in error. Due to this fact, as later experiments proved, the Nicol prism measurements were all in error at the time the data for curve 4 were obtained.

To eliminate these difficulties, the following method was devised for obtaining the zero readings of the Nicol prisms.

Suppose that the telescope and collimator are adjusted so that light is reflected from a water (or glass) surface at the Brewster angle of incidence. If the polarizer Nicol is turned so that the incident light is polarized in the plane of incidence, almost no light will be reflected. If the angle of incidence is varied slowly from values a little less than the Brewster angle to values slightly larger, the azimuth angle $A$ of the analyzer Nicol, when set to quench the reflected light, will remain constant, since what little light is reflected will be plane polarized in the plane of incidence.

If the plane of polarization of the incident light were inclined very slightly with the plane of incidence, there would be a very small component normal to the plane of incidence. With the angle of incidence $I$ several degrees removed from the Brewster angle, this normal component would have little effect on the azimuth angle $A$. However, as the Brewster angle of incidence is approached, the normal component becomes an appreciable fraction of the parallel component, and $A$ will increase (or decrease, depending on the inclination of the plane of polarization of the incident light), the rate of change increasing rapidly as the Brewster angle is approached. When $I$ passes through the Brewster angle, $A$ shifts to negative (or positive) values, and then decreases in magnitude as $I$ is changed still more. The test is very sensitive, but is fatiguing to the eyes because of the minute quantities of light involved.

After the zero readings were determined by this method, observations were repeated on mercury surfaces, with the results shown by curve 6, Fig. 2. The change of the index of refraction with the angle of incidence has been eliminated almost entirely. Curves 7 and 8 show the small variation in the values of the index of refraction of other metallic mirrors with changes of the angle of incidence. The mirror for curve 7 was thought to be silver. The index of refraction for this mirror is considerably higher than that usually given for silver. It is very probable that this is caused by impurities in the silver. Curve 8 is a mean curve for a number of sputtered platinum mirrors.

Since the slope of curve 4 was due to instrumental errors, it might be that some of the variations of the optical constants which have been previously found by other observers were caused by errors of a similar nature.

TABLE I. *Optical constants.*

| Mercury surface, corresponding to curve 4, Fig. 2. | | | | | |
|---|---|---|---|---|---|
| $I$ | 30° 49′ | 41° 30′ | 51° 6′ | 66° 51′ | 82° 53′ |
| $\theta$ | −49 14 | −50 17 | −51 12 | −54 24 | −53 51 |
| $\varphi$ | −7 30 | −13 54 | −21 52 | −47 27 | −119 8 |
| $N$ | 2.73 | 2.38 | 2.23 | 1.95 | 1.67 |
| $K_0$ | 2.05 | 2.95 | 3.68 | 4.07 | 4.41 |

| Mercury surface, corresponding to curve 6, Fig. 2. | | | |
|---|---|---|---|
| $I$ | 43° 12′ | 58° 4′ | 71° 54′ |
| $\theta$ | −47 26 | −49 50 | −53 10 |
| $\varphi$ | −15 36 | −32 9 | −63 25 |
| $N$ | 1.367 | 1.408 | 1.458 |
| $K_0$ | 4.21 | 4.23 | 4.275 |

[16] J. C. M'Connel, Phil. Mag. [5] **19**, 317 (1885).

Curve 1 shows little variation with the angle of incidence, while curve 2 shows a marked variation. This, as well as the difference in the shapes of curves 4 and 5, illustrates a point which was discovered in the investigation of Eq. (55) for the effect of errors of measurement, namely; the effect of a given error depends on the experimental conditions. Apparently, the instrumental errors which caused the variation shown by curve 2 had little effect on values of the index (and absorption coefficient) of the magnitude exhibited by rubidium.

## Film Measurements

To investigate the possibility of apparent variation of film thickness with the angle of incidence, polarimetric observations were made on several metallic films sputtered on glass. To simplify the computations as much as possible, observations were made always at the same angles of incidence, 45°, 60° and 75°. Table II gives the computed film thicknesses $\zeta$, expressed in angstrom units. The first film was silver; the second and third were platinum.

The results are shown graphically in Fig. 3. The real parts of the computed thicknesses have been plotted as ordinates, and the angles of incidence as abscissae. All curves show a change in the computed film thickness, the thickness consistently increasing with the angle of incidence. Furthermore, this variation persists, whether average values of the optical constants or the values determined at a given angle of incidence are used in computing the film thickness.

That the film thickness determined by the polarimetric method was of the correct order of magnitude was roughly checked by computing the thickness of the film from its area and mass. In each case, the glass was weighed before and after the film was formed. Since the area covered by the film was small, the total mass of the film was exceedingly minute, of the order of magnitude of $10^{-5}$ grams. The weighing was accomplished by using a procedure described by Conrady.[17] For the thinnest film, another check was made on its thickness by controling the time of sputtering. It is interesting to note that the range of values of the thickness of film 3 compares favorably with the value of the diameter of a platinum atom, 2.6–3.3 A, given by Lunnon.[18]

Table II.

| $I$ | 45° | 60° | 75° | By weight |
|---|---|---|---|---|
| $\zeta_1$ | $43.5-i\,26.9$ | $57.9-i\,49.2$ | $67.7-i\,53.7$ | 60 |
| $\zeta_2$ | $12.7-i\,1.31$ | $25.7-i\,15.2$ | $33.5-i\,17.8$ | 40 |
| $\zeta_3$ | $2.30-i\,2.23$ | $3.22-i\,6.96$ | $3.29-i\,7.51$ | 10 |

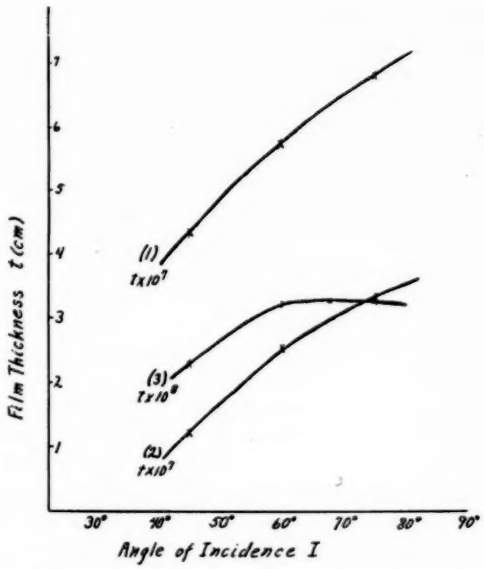



Fig. 3. Variation of computed film thickness with angle of incidence.

One other point was found concerning the film measurements, namely; in each case the film thickness, determined by the polarimetric method, was computed to be a complex quantity. Because of the nature of the computations, this fact in itself is not surprising. However, in all cases, the imaginary component was negative and of the same order of magnitude as the real component. The graphs given by Ives and Johnsrud confirm the apparent variation of film thickness with the angle of incidence. If their work is referred to, it will be noticed that a smooth curve drawn through the points plotted from their observed data will intersect the isothickness curves. This clearly indicates that the

[17] A. E. Conrady, Proc. Roy. Soc. **101**, 211 (1922).
[18] R. G. Lunnon, Proc. Phys. Soc. **38**, 95, 105 (1925–6).

apparent thickness of their rubidium film changed with the angle of incidence and most likely was complex in nature. The theory of thin films is much more complicated than that for bulk materials. In fact, some questionable assumption, e.g., that a thin film has a continuous structure, seems to be necessary to make the theory of thin films tractable. Even with such an assumption, film thicknesses computed from polarimetric data have been found to be of the correct order of magnitude. The apparent variation of the computed film thicknesses with the angle of incidence must result from a detectable difference between the properties of thin films and those of bulk materials.

In conclusion, the writer wishes to take this opportunity to thank the friends who have aided him in his work, especially Professors H. M. Reese and R. T. Dufford, of the department of physics.

# A Simple Azimuth and Phase Half-Shade of Variable Sensitivity

C. V. KENT, *Blake Hall, Kansas University, Lawrence, Kansas*

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The azimuth half-shade component consists of two thin adjoining glass plates mounted on and in front of the analyzer at an angle of about 90° with each other. The common edge is in the plane of polarization of the analyzer, the glass strips making equal angles with this plane. The phase half-shade component is an approximately quarter-wave mica plate placed in front of the glass slips (away from the analyzer), its planes of polarization being in and perpendicular to that of the analyzer. It is so cut and mounted that its free edge bisects the field of view in a line perpendicular to the common edge of the glass slips. End-point setting is complete when (1) the intensities in adjacent quadrants in the field of view *not* back of the mica phase plate are equal (azimuth), and (2), they are also equal in the quadrants back of the mica. Azimuth and phase sensitivity are both varied equally by changing the angle of inclination of the common edge of the glass slips with the axis of rotation of the analyzer. Due to the method of construction, all adjustments for proper operation can be made optically at any time. No high constructive skill is needed in making the apparatus and the preliminary adjustments are not critical. The photometric dividing line between quadrants for both settings (1) and (2) is one obtuse adjoining edge of one of the glass slips which is easily made imperceptible. The sensitivity in both azimuth and phase is equal to that of any of the usual variable sensitivity half-shade devices.

ACCURATE determination of the crossed position of an analyzer in plane-polarized light requires the use of some sort of half-shade device, or in more convenient terminology, an "azimuth bifield." When elliptically polarized light is analyzed, it is first reduced to plane-polarized light by a phase compensator, and it is equally imperative in this case to use a "phase bifield." Since bifields do not seem to be generally available, except as parts of specialized apparatus, it seems worth while to describe a simple combination of both, equal in sensitivity and accuracy to any of the more complicated and expensive types.

The azimuth bifield (Fig. 1–a) (invented by Poynting[1] and mentioned briefly by the writer[2]) consists of two strips of strain-free glass *B*, each about 20×6×1.5 mm cut from a tested microscope slide. These are mounted on, and immediately in front of, the analyzer *A*, with one long edge of each in contact, their faces being inclined at an angle of about 90° with each other. The common contact edge is in the plane of polarization of the analyzer (or in the plane perpendicular to it) and inclined at an angle to the direction of the light beam as shown in Fig. 1, the field of view being divided into equal halves by the common edge.

*D*, the phase bifield, is a mica plate with approximately 90° phase difference, its planes of vibration being in and perpendicular to the plane of vibration of the analyzer. It is fastened to a brass ring in an annular bearing so that it covers the lower half of the field of view.

The common edge between the glass slips is the only photometric dividing line, serving for both the upper and lower pairs of quadrants. It is easily made imperceptible by wet grinding one obtuse angle edge of one of the glass slips

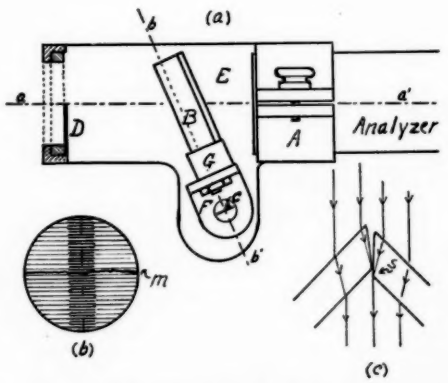


FIG. 1. (*a*) Bifield mounting. *A*, collar on analyzer tube; *B*, glass bifield; *C*, axis of variable sensitivity rotation; *D*, phase bifield; *E*, brass bar from collar *A*; *F*, right angle metal piece held by spring washer and thumb nut on back against *E*; *G*, metal cup in which glass slips are cemented, held on shelf of *F* by lock nut on stud; *aa'*, axis of light beam; *bb'* axis of rotation of *B*. (*b*) Field of view in the balanced position; *m*, mica edge. (*c*) Cross section of glass slips, showing position of sharp dividing edge, *s*.

[1] J. H. Poynting, *Collected Scientific Papers* (Cambridge, 1920), pp. 463–464.

[2] C. V. Kent, Phys. Rev. **14**, 463 (1919).

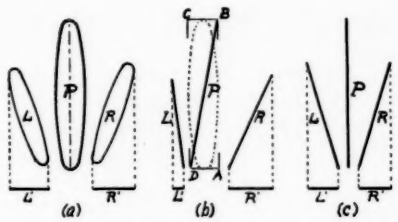


FIG. 2. Action of mica half-shade. (*a*) Action of glass bifield alone; *P*, light from compensator; *R* and *L*, light transmitted by right and left glass slips, respectively; *R'* and *L'*, amplitudes of light transmitted from respective glass slips through analyzer. (*b*) Action of mica phase plate, condition (*a*) holding. *R*, *L*, *R'* and *L'* as before. (*c*) Condition at balance.

very sharp and offsetting it nearer the analyzer, as shown in Fig. 1–c. The other three edges are completely hidden behind it, as shown. An eyepiece is usually focused on this edge.

In making an end-point setting, analyzer and compensator are first adjusted for minimum illumination and photometric equality between the two quadrants *not* behind the mica plate. Keeping this equality, the compensator reading is varied until the intensities in the quadrants *behind* the mica plate are also matched, completing the end setting. The field of view (Fig. 1–b) consists of two sharply defined dark strips adjacent to the dividing line, bordered by brighter areas of multiple reflection. The dark strips are the sensitive areas.

The preliminary adjustments for correct operation are all optical. The compensator and mica half-shade are removed, the glass bifield swung out of the field of view and the analyzer turned to the extinction azimuth in intense, plane-polarized light. The glass bifield is then rotated (on axis *C*) until the common edge *bb'* is perpendicular to the axis *aa'* and the collar rotated on the analyzer tube until the field of view through the glass slips is also black. The collar is then clamped, holding the edge *bb'* thereafter in the plane of polarization of the analyzer. The bifield is next inclined so that *bb'* is not perpendicular to *aa'* and the slip mounting rotated (on axis *bb'*) to a position where the halves of the field of view are photometrically matched, and then clamped. The faces of the glass slips now make equal angles with the plane of polarization of the analyzer. The mica plate is put into position and rotated until equality of illumination is secured in the two quadrants back of it, finishing the adjustment. The sensitivity is varied at any time by changing the angle of inclination of *bb'* with *aa'*.

The action of the glass azimuth bifield in plane-polarized light has been explained elsewhere.[1, 2] It seems hardly possible that the use of a quarter-wave plate as a half-shade device in the manner here adopted has not appeared somewhere in the literature on the subject, but so far, the writer has not encountered it. After the preliminary adjustment to minimum illumination, the light from the compensator may be represented by the narrow ellipse *P* of Fig. 2–a. Its two components in and perpendicular to the plane of incidence on one of the glass plates are unequally diminished with no phase change by transmission through it and form a smaller ellipse *R*, inclined at a small angle to *P*. Equality of illumination will obtain in the quadrants not back of the mica plate when the dividing line is parallel to the major axis of *P*; in this case, the light through the other plate is represented by an ellipse *L*, precisely similar to *R* but inclined equally in the opposite direction from *P*, *R'* and *L'* being the equal amplitudes of *R* and *L*, respectively, which traverse the analyzer. The analyzer setting has the high accuracy of the half-shade method, being practically unaffected by the slight departures of *R* and *L* from plane-polarized light. Conversely, therefore, the compensator setting at this stage of the adjustments has the low accuracy of a minimum illumination setting of 1° or 2°.

The mica quarter-wave plate, however, transforms the elliptically polarized light *P*, passing through it into plane-polarized light *DB* (or *AC*) of Fig. 2–b. The quadrants back of the mica plate are then *unequally* illumined since this direction is not in the plane of polarization of the analyzer, and can be balanced only when the component *CB* is made to vanish by readjusting the compensator. When so balanced *P* is related to the light entering the analyzer, *R* and *L*, as in Fig. 2–c.

It is not difficult to show that the phase sensitivity of the mica-glass combination is the same as the azimuth sensitivity of the glass bifield in plane-polarized light—a few minutes of arc. Both azimuth and phase sensitivity are

equally changed by varying the inclination of the glass bifield—a convenient circumstance, since both are limited in the same manner by the stray light present.

This half-shade device has the great advantages of negligible cost of materials and simplicity of construction and adjustment combined with the high, variable sensitivity of other half-shade devices. Its low cost makes it an appropriate concomitant for accurate work when Polaroid or similar materials are used in place of Nicol prisms. The present laboratory construction might be improved by mounting the device in a short, protecting tube and making the preliminary adjustments for correct operation more or less permanent.

My thanks are due to Mr. Louis Wolfson for his careful work in testing the apparatus.

# A Polaroid Half-Shade Analyzer

A. H. PFUND, *Johns Hopkins University, Baltimore, Maryland*

(Received September 30, 1936)

By cementing a half-wave plate of Cellophane over a portion of a sheet of Polaroid, two fields, separated by a photometric line of demarcation are produced. Since the directions of vibration of the polarized light in the two fields are mutually perpendicular, a sensitive device for the detection of polarized light is realized.

THIS simple device for demonstrations is made from a 1- to 2-inch square of Polaroid so cut that the direction of vibration of the transmitted light is parallel to one of the edges of the square. Several pieces of Cellophane of the kind used as cigar wrappers, are examined individually between parallel Nicols. As is well known, Cellophane is doubly refracting—the two directions of vibration running, respectively, parallel and perpendicular to the fine creases or lines shown by sheets of Cellophane. With the creases at an angle of 45° with the direction of the polarized light, the sheet which appears the darkest purple between parallel Nicols is chosen. From this sheet, which in reality is a half-wave plate for green light, a square of the same size as the Polaroid is cut in such a manner that the diagonal is parallel to the fine creases in the Cellophane. With sharp scissors this square is cut in two along the diagonal and one of the halves is laid on the square of Polaroid so that the diagonal edge of the Cellophane coincides with the diagonal of the square. A minute amount of glue at the corners serves to hold the two sheets in place. This system is mounted between strain-free sheets of eighth-inch plate glass. In the place of Canada balsam, polymerized linseed oil is used as cement. After having coated all surfaces as thoroughly as possible, the system is assembled and the excess oil is squeezed out. If the plates be allowed to lie in a horizontal position for several hours, all imprisoned air bubbles work their way out to the edges. After having removed all excess oil it is found that, after a few days, the oil will have oxidized or "dried" around the edges. Plates of the above type, made more than a year ago, show no trace of deterioration.

If this plate be held a foot or more from the eye with the Cellophane away from the observer, it is found that for partially or completely polarized incident light, the two halves of the analyzer are markedly different in brightness. Upon viewing the blue sky through the analyzer, it is found that the halves become alternately bright and dark as the plate is rotated in its own plane. Because of the excellence of the edge of the Cellophane, it is possible to find a position of the plate in which the edge disappears as completely as in a good photometer. It is not improbable that this analyzer will rival the Savart plate in its ability to detect the admixture of small amounts of polarized light to ordinary light. The analyzer may also be used for demonstration polarimeters and for the making and testing of quarter-wave plates. Whenever color differences between the two halves of the field become annoying it is merely necessary to interpose a green color filter.

# Author Index to Volume 26

(References with (A) are to abstracts of papers presented at meetings of the Optical Society of America.)

**Alvarez, Luis W.** Diffraction grating at grazing incidence—343

**Atanasoff, J. V. and A. E. Brandt.** Application of punched card equipment to the analysis of complex spectra—83

**Balinkin, I. A. and D. A. Wells.** Spectrum of rubidium in the mercury arc—77

**Barnes, B. T. and W. E. Forsythe.** Spectral radiant intensities of some tungsten filament incandescent lamps—313

**Barnes, R. Bowling and Lyman G. Bonner.** Filters for the infrared—428

**Bear, Richard S. and Francis O. Schmitt.** Measurement of small retardations with the polarizing microscope—363

——— Optics of nerve myelin—206

**Benford, Frank.** Monochromator for the near ultraviolet—99

**Bonner, Lyman G.** (see Barnes, R. Bowling)—428

**Boyce, J. C. and H. A. Robinson.** Wave-length identification lists for the extreme ultraviolet—133

**Brandt, A. E.** (see Atanasoff, J. V.)—83

**Briggs, H. B.** (see Ives, Herbert E.)—238, 247

**Clarke, George L.** (see Powell, Wilson M.)—111

**Easley, Miss M. A.** (see Forsythe, W. E.)—310

**Emberson, Richard M.** Method for making and testing quarter-wave plates—63

——— Polaroid half-shade analyzer—434

**Estey, Roger S.** Design of color temperature altering filters—304(A)

——— Selection of color temperature altering filters—293

**Ferree, C. E. and G. Rand.** Effect of length of exposure of the test object on visual acuity. A correction—272

**Focke, Alfred B.** Quantitative study of the improvement of speculum gratings by the application of aluminum—235

**Fonda, Gorton R.** Fluorescence of rhodamine—316

**Forsythe, W. E. and Miss M. A. Easley.** Photographic effectiveness of the radiation from a number of photographic sources—310

——— (see Barnes, B. T.)—313

**Foster, Leon V.** Polarizing vertical illuminator—224(A)

**Fowler, R. Dudley** (see Smith, A. E.)—79

**Freeman, Ellis.** Intensity, area, and distance of visual stimulus. A correction—271

**Gallup, John.** Vacuum cell luminescence microscope and its use in the study of luminescent materials—213

**Garrett, Milan W.** (see Wright, Winthrop R.)—360

**Gaviola, E.** On the quantitative use of the Foucault knife-edge test—163

——— (see Strong, John)—153

**Gibson, Kasson S., Geraldine Walker Haupt and Harry J. Keegan.** Standardization and specification of railway signal colors—226(A)

**Granath, L. P. and R. K. Stranathan.** Hyperfine structure spectrograph—279

**Griggs, Henry P.** Low intensity solarization for four emulsions—384

**Haig, Charles** (see Hecht, Selig)—304(A)

**Hardy, A. C.** Subscriptions to *The Review of Scientific Instruments*—427

**Haupt, Geraldine Walker** (see Gibson, Kasson S.)—226(A)

**Hecht, Selig and Charles Haig.** Dark adaptation as influenced by intensity of light adaptation—304(A)

——— **and Simon Shlaer.** Saturation as the basis for color mixture in the color-blind—226(A)

**Henry, D. E.** (see Rentschler, H. C.)—30

**Herzberger, M.** An interesting optical law—205

——— Erratum: Theory of microscope vision—196

——— First-order laws in asymmetrical optical systems. Part I. The image of a given congruence: Fundamental conceptions—354

——— First-order laws in asymmetrical optical systems. II. The image congruences belonging to the rays emerging from a point in object and image space: Fundamental forms—389

——— New theory of optical image formation—197, 305(A)

——— On the characteristic function of Hamilton, the eiconal of Bruns, and their use in optics—177

——— Simplified theory of the image errors according to L. Seidel—35

——— Theory of microscope vision—52

**Hilberry, Norman.** Theory of the multiple diffraction grating—1

**Holmes, F. T.** Separation of close spectral lines by the method of anomalous dispersion—365

**Hopfield, John J. and George B. Watkins.** Refraction of tempered plate glass—24

**Hoyt, A.** New type of interferometer—262

**Hubing, Grover F.** Portable blocking-layer photo-cell pyrometer—260

**Hudson, J. Cramer.** Necrology: William Duane—75

**Hulbert, E. O.** Sextant with improved filters—216, 305(A)

**Hunter, Richard S.** Estimation of gloss with a luminous target—304(A)

——— Gloss investigations using reflected images of a target pattern—190

——— Identification of five different types of gloss effects—224(A)

——— Null method photoelectric reflectometer—225(A)

**Ingersoll, L. R.** Necrology: Charles Elwood Mendenhall—75

———, **J. G. Winans and E. H. Krause.** Polarizing characteristics of polaroid plates for wave-lengths 4000A to 20,000A—233

**Ives, Herbert E. and H. B. Briggs.** Calculated and experimental photoelectric emission from thin films of potassium—247

——— Optical constants of potassium—238

**Jones, Loyd A. and M. E. Russell.** Minimum useful gradient as a criterion of photographic speed—228(A)
**Jorgensen, Wilhelm** (see Utterback, C. L.)—257
**Judd, Deane B.** Calibration and use of a subtractive colorimeter for small chromaticity differences on the standard ICI system—304(A)
——— Changes in color temperature of tungsten-filament lamps at constant voltage—409
——— Estimation of chromaticity differences and nearest color temperature on the standard 1931 ICI colorimetric coordinate system—421
——— Subtractive colorimeter for the measurement of small chromaticity differences between surfaces of moderate spectral selectivity of reflectance—225(A)

**Kabakjian, D. H.** Decay of luminescence in solid solutions—229(A)
**Keegan, Harry J.** (see Gibson, Kasson S.)—226(A)
**Kent, C. V.** Simple azimuth and phase half-shade of variable sensitivity—450
**Kingslake, R.** Measurement of the aberrations of a microscope objective—224(A), 251
**Krause, E. H.** (see Ingersoll, L. R.)—233

**Loveland, R. T.** Optics of low power photomicrography—224(A)
**Lowry, E. M.** Instrument for the measurement of the graininess of photographic materials—65, 227(A)
**Lü, Ta-Yuan** (see Ny, Tsi-Zé)—26
**Luckiesh, Matthew and Frank K. Moss.** Rational visibility meter—227(A)
**Lyons, William James.** Behavior of the 4930A absorption band of uranine solutions under high pressure—144
——— **and Franklin E. Poindexter.** Spectrometer for studies at high pressures—146

**Miles, Walter R.** Centers of ocular rotation and other characteristics of vertical and horizontal eye movements 226(A)
**Mohler, Nora M.** Photographic penetration of haze—219
——— **and Delia Ann Taylor.** Photovoltaic cell reflection densitometer—386
**Morton, G. A.** (see Zworykin, V. K.)—181
**Moss, Frank K.** (see Luckiesh, Matthew)—227(A)
**Müller, R. H. and A. Spector.** Balanced circuits employing barrier-layer photoelectric cells—305(A)

**Needham, George** (see Wetzel, R. A.)—224(A)
**Nichols, E. L. and C. L. Stanford.** Hydrogen effect in certain oxides—91
**Norman, Daniel.** Effect of pre-exposure in spectrum photography—407
**Ny, Tsi-Zé and Ta-Yuan Lü.** Pressure effect on sensitivity of different photographic films—26

**O'Brien, Brian** (see Russell, T. A.)—231(A)
**O'Bryan, H. M.** Dispersion of several metals in the visible region—230(A)
——— Optical constants of several metals in vacuum—122
**Ogle, Kenneth N.** Correction of aniseikonia with ophthalmic lenses—323

**Pegram, G. B.** Necrology: Michael Idvorsky Pupin—76
**Perrin, Fred H.** Simple criterion for the absence of secondary spectrum—230(A)
**Pfund, A. H.** Electric Welsbach lamp—439
——— Infrared dispersion of selected liquids and solids—230(A)
——— Polaroid half-shade analyzer—453
**Plummer, Jesse H.** Transmissions of powder films to the infrared spectrum—434
**Plyler, E. K.** (see Williams, Dudley)—149
**Poindexter, Franklin E.** (see Lyons, W. James)—146
**Powell, Wilson M. and George L. Clarke.** Reflection and absorption of daylight at the surface of the ocean—111

**Rand, G.** (see Ferree, C. E.)—272
**Razek, Joseph.** Aid to the calculation of tristimulus specifications—225(A)
**Rentschler, H. C. and D. E. Henry.** Effect of oxygen upon the photoelectric thresholds of metals—30
**Robinson, H. A.** (see Boyce, J. C.)—133
**Roger, Henry** (see Wetzel, R. A.)—224(A)
**Russell, M. E.** (see Jones, Loyd A.)—228(A)
**Russell, T. A. and Brian O'Brien.** Mechanism of deposition of evaporated metal films exhibiting optical resonance—231(A)

**Schmitt, Francis O.** (see Bear, Richard S.)—206, 363
**Schneider, Edwin G.** Coloration of lithium fluoride by glow discharge and some practical applications—305(A)
**Shaw, R. William.** Fuertes observatory ultraviolet stellar spectrograph—273
**Sheard, Charles.** Measurements on the tolerance to light in nonphotophobic individuals and in certain pathological conditions—227(A)
**Sheppard, S. E., T. Russell Wilkins, E. P. Wightman and R. N. Wolfe.** Temperature coefficient of photographic sensitivity. Part II. Effect of low temperature on the photographic action of $\alpha$-particles—228(A)
**Shlaer, Simon** (see Hecht, Selig)—226(A)
**Silberstein, Ludwik.** Corrigenda to "A simplified computation of Cartesian lens surfaces"—131
**Simeon, F.** (see Twyman, F.)—121
**Smith, A. E. and R. Dudley Fowler.** Low voltage source of ultraviolet continuum—79
**Spector, A.** (see Müller, R. H.)—305(A)
**Stanford, C. L.** (see Nichols, E. L.)—91
**Stranathan, R. K.** (see Granath, L. P.)—279
**Strong, John.** On a method of decreasing the reflection from nonmetallic substances—73
——— Transmission curves for the new polarizers—256
——— **and E. Gaviola.** On the figuring and correcting of mirrors by controlled deposition of aluminum—153

**Taylor, Delia Ann** (see Mohler, Nora M.)—386
**Tietz, W. J.** Necrology: C. W. Robbins—131
**Tuttle, Clifton.** Recording physical densitometer—282
**Twyman, F. and F. Simeon.** On the refractive index changes in optical glass occasioned by chilling and tempering—121

**Uhler, Horace S.** Approximations to the Cartesian oval—128
——— Extension of the domain of validity of the general formula for oblique deviation—89
**Utterback, C. L. and Wilhelm Jorgensen.** Scattering of daylight in the sea—257

**van Kreveld, A.** Objective measurements of graininess of photographic materials—170

**Walerstein, I. and R. A. Woodson.** Multiple sets of fringes in the Michelson interferometer—267
**Watkins, George B.** (see Hopfield, John J.)—24
**Watson, William W.** (see Weber, Robert L.)—307
**Weatherford, R. D.** (see Williams, Dudley)—149
**Weaver, K. S.** Calculation of filters for color temperature conversion—339
**Webb, J. H.** Photographic intermittency effect in the region of extremely short flash periods—347
——— Photographic latent image considered from the standpoint of the quantum mechanics model of crystals—367
——— Summation of different color radiations by a photographic emulsion—12, 228(A)
**Weber, Robert L. and William W. Watson.** Ultraviolet wave-length standards of N, C, and O, λ2300 to λ1080—307
**Wells, D. A.** (see Balinkin, I. A.)—77
**Wetzel, R. A., George Needham and Henry Roger.** Ultramicroscope in motion picture—224(A)
**Wightman, E. P.** (see Sheppard, S. E.)—228(A)
**Wilkins, T. Russell** (see Sheppard, S. E.)—228(A)
——— (see Wolfe, R. N.)—105, 223(A)
**Williams, Dudley, R. D. Weatherford and E. K. Plyler.** Infrared absorption spectra of mixtures of alcohol and water—149
**Winans, J. G.** (see Ingersoll, L. R.)—233
**Witmer, Enos E.** Second law of thermodynamics as applied to optics—229(A)
**Wolfe, Robert N. and T. Russell Wilkins.** Spurious photographic reciprocity defect for alpha-rays—228(A)
——— Validity of the photographic reciprocity law for alpha-rays—105
——— (see Sheppard, S. E.)—228(A)
**Woodson, R. A.** (see Walerstein, I.)—267
**Wright, F. E.** Plane polarization in sunlight reflected by nonpolished surfaces—230(A)
**Wright, Winthrop R. and Milan W. Garrett.** Verification of the Huygens wave surfaces in uniaxial crystals—360

**Zworykin, V. K. and G. A. Morton.** Applied electron optics—181

# Analytic Subject Index to Volume 26

(References with (A) are to abstracts of papers presented at meetings of the Optical Society of America; (T) designates title only.)

**Absorption, including absorption spectra**
Behavior of the 4930A absorption band of uranine solutions under high pressure, W. J. Lyons—144
Infrared absorption spectra of mixtures of alcohol and water, D. Williams, R. D. Weatherford and E. K. Plyler—149
Reflection and absorption of daylight at the surface of the ocean, W. M. Powell and G. L. Clarke—111
Transmissions of powder films to the infrared spectrum, J. H. Plummer—434

**Biological (phenomena and measurements)**
Measurement of small retardations with the polarizing microscope, R. S. Bear and F. O. Schmitt—363
Measurements on the tolerance to light in nonphotophobic individuals and in certain pathological conditions, C. Sheard—227(A)
Messages from sense organs, D. W. Bronk—221(T)
Optics of nerve myelin, R. S. Bear and F. O. Schmitt—206

**Color and colorimetry** (see also **Absorption, including absorption spectra**)
Aid to the calculation of tristimulus specifications, J. Razek—225(A)
Calibration and use of a subtractive colorimeter for small chromaticity differences on the standard ICI system, D. B. Judd—304(A)
Coloration of lithium fluoride by glow discharge and some practical applications, E. G. Schneider—305(A)
Saturation as the basis for color mixture in the color-blind, S. Hecht and S. Shlaer—226(A)
Standardization and specification of railway signal colors, K. S. Gibson, Geraldine Walker Haupt and H. J. Keegan—226(A)
Subtractive colorimeter for the measurement of small chromaticity differences between surfaces of moderate spectral selectivity of reflectance, D. B. Judd—225(A)

**Color temperature**
Calculation of filters for color temperature conversion, K. S. Weaver—339
Changes in color temperature of tungsten-filament lamps at constant voltage, D. B. Judd—409
Design of color temperature altering filters, R. S. Estey—304(A)
Estimation of chromaticity differences and nearest color temperature on the standard 1931 ICI colorimetric coordinate system, D. B. Judd—421
Selection of color temperature altering filters, R. S. Estey—293

**Crystals, properties of** (see also **X-Rays**)
Verification of the Huygens wave surfaces in uniaxial crystals, W. R. Wright and M. W. Garrett—360

**Densitometry**
Photovoltaic cell reflection densitometry, Nora M. Mohler and Delia Ann Taylor—386
Recording physical densitometer, C. Tuttle—282

**Diffraction gratings**
Developments in the rulings of gratings at the University of Chicago, H. G. Gale—302(T)
Diffraction grating at grazing incidence, L. W. Alvarez—343
Diffraction grating supply and demand, R. C. Gibbs—302(T)
Early history of the diffraction grating, K. K. Darrow—302(T)
Joint symposium on the diffraction grating—302
On the ruling and testing of diffraction gratings, R. W. Wood—302(T)
Quantitative study of the improvement of speculum gratings by the application of aluminum, A. B. Focke—235
Theory of the multiple diffraction grating, N. Hilberry—1

**Dispersion**
Dispersion of several metals in the visible region, H. M. O'Bryan—230(A)
Infrared dispersion of selected liquids and solids, A. H. Pfund—230(A)
Separation of close spectral lines by the method of anomalous dispersion, F. T. Holmes—365

**Electrical measurements**
Balanced circuits employing barrier-layer photoelectric cells, R. H. Müller and A. Spector—305(A)

**Films**
Mechanism of deposition of evaporated metal films exhibiting optical resonance, T. A. Russell and B. O'Brien—231(A)

**Filters** (see also **Absorption, including absorption spectra**)
Design of color temperature altering filters, R. S. Estey—304(A)
Filters for the infrared, R. B. Barnes and L. G. Bonner—428
Selection of color temperature altering filters, R. S. Estey—293

**Infrared**
Filters for the infrared, R. B. Barnes and L. G. Bonner—428
Transmissions of powder films to the infrared spectrum, J. H. Plummer—434

**Interference of light and interferometry**
Multiple sets of fringes in the Michelson interferometer, I. Walerstein and R. A. Woodson—267
New type of interferometer, A. Hoyt—262

**Ives Medal**
The Frederic Ives medal—221

**Lenses and mirrors**
On the figuring and correcting of mirrors by controlled deposition of aluminum, J. Strong and E. Gaviola—153
On the quantitative use of the Foucault knife-edge test, E. Gaviola—163
**Light sources, properties and measurements**
Electric Welsbach lamp, A. H. Pfund—439
Low voltage source of ultraviolet continuum, A. E. Smith and R. D. Fowler—79
Monochromator for the near ultraviolet, F. Benford—99
Polarizing vertical illuminator, L. V. Foster—224(A)
**Luminescence**
Decay of luminescence in solid solutions, D. H. Kabakjian—229(A)
Fluorescence of rhodamine, G. R. Fonda—316
Hydrogen effect in certain oxides, E. L. Nichols and C. L. Stanford—91
Vacuum cell luminescence microscope and its use in the study of luminescent materials, J. Gallup—213

**Methods and instruments, general**
Sextant with improved filters, E. O. Hulburt—216; 305(A)
**Microscopy; microscopes**
Dark field and ultra microscopes, S. H. Gage—221(T)
Electron microscopes, C. J. Davisson—221(T)
Geometrical optics of the microscope, W. B. Rayton—221(T)
Illumination and manipulation of the microscope, H. W. Zieler—221(T)
Mechanical design of the microscope, H. F. Kurtz—221(T)
Measurement of the aberrations of a microscope objective, R. Kingslake—224(A), 251
Microscope and microscopy, sessions devoted to papers on—221
Polarizing microscopes, L. C. Graton—221(T)
Theory of microscope vision, M. Herzberger—52, (erratum) 196, 221(T)
Ultra-microscope in motion picture, R. A. Wetzel, G. Needham and H. Roger—224(A)

**Necrology**
William Duane—75
Charles Elwood Mendenhall—75
Michael Idvorsky Pupin—76
C. W. Robbins—131

**Optical Society of America**
Announcements by secretary—222
Annual report of editor of publications, for 1934, with changes since January 1, 1935—221(T)
Annual report of secretary for 1934 with changes since January 1, 1935—221(T); 1935, 298
Annual report of treasurer for 1934, with changes since January 1, 1935—221(T); 1935, 300
Appointments of committees, 1936—302
Appointment of Committee on Qualifications for Membership—222
Appointment of representative and alternate on the American Standards Association Sectional Committee on Safety Glass—222
Appointment of representative on the American Standards Motion Picture Sectional Committee—222
Appointment of representatives on Inter-Society Color Council—222
Appointment of six associate editors for a term of six years beginning January 1, 1936—223
Appointment of tellers to make count of ballots for 1935 election of officers and directors—222; Report—223
Appointment of voting delegates on Inter-Society Color Council—222
Business session—221
Joint symposium on the diffraction grating—302
Meeting with joint Philadelphia Physics Symposium—221
Microscope and microscopy, sessions devoted to papers on—221
Minutes of the sixth meeting of the Directors—222
Minutes of the seventh meeting of the Directors—302
Nomination and appointment of representatives—303
Physical basis of sensation, invited papers on—221(T)
Proceedings of the New York meeting, February 21, 1936—302
Proceedings of the twentieth annual meeting, The Franklin Institute, Philadelphia, Pa., October 24–26, 1935—221
Program of contributed papers—224, 304
Reappointment of C. L. Bausch as representative on Division of Physical Sciences, National Research Council—222
Reappointment of P. I. Wold as representative in the American Association for the Advancement of Science—222
Report of representative at conference on standards for inspection of motor vehicles—223
Resolution to purchase one subscription to R. S. I. for each member entitled to receive J. O. S. A.—223
Subscriptions to The Review of Scientific Instruments, A. H. Hardy—427
Transfer from associate to regular membership—222
**Optical constants** (see **Optics, physical**)
**Optics, electron**
Applied electron optics, V. K. Zworykin and G. A. Morton—181
Electron microscopes, C. J. Davisson—221(T)
**Optics, geometrical**
Approximations to the Cartesian oval, H. S. Uhler—128
Extension of the domain of validity of the general formula for oblique deviation, H. S. Uhler—89
First-order laws in asymmetrical optical systems. Part I. The image of a given congruence: Fundamental conceptions, M. Herzberger—354. Part II. The image congruences belonging to the rays emerging from a point in object and image space: Fundamental forms—389
Geometrical optics of the microscope, W. B. Rayton—221(T)
Interesting optical law, M. Herzberger—205

**Optics, geometrical** (continued)
New theory of optical image formation, M. Herzberger —197, 305(A)
On the characteristic function of Hamilton, the eiconal of Bruns, and their use in optics, M. Herzberger—177
Simplified computation of Cartesian lens surfaces, L. Silberstein, Corrigenda—131
Simple criterion for the absence of secondary spectrum, F. H. Perrin—230(A)
Simplified theory of the image errors according to L. Seidel, M. Herzberger—35

**Optics, physical**
Optical constants of potassium, H. E. Ives and H. B. Briggs—238
Optical constants of several metals in vacuum, H. M. O'Bryan—122
Polarimetric determination of optical properties, R. M. Emberson—443

**Photoelectric phenomena**
Calculated and experimental photoelectric emission from thin films of potassium, H. E. Ives and H. B. Briggs—247
Effect of oxygen upon the photoelectric thresholds of metals, H. C. Rentschler and D. E. Henry—30

**Photography, including cameras**
Effect of pre-exposure in spectrum photography, D. Norman—407
Instrument for the measurement of the graininess of photographic materials, E. M. Lowry—65; 227(A)
Low intensity solarization for four emulsions, H. P. Griggs—384
Minimum useful gradient as a criterion of photographic speed, L. A. Jones and M. E. Russell—228(A)
Objective measurements of graininess of photographic materials, A. van Kreveld—170
Optics of low power photomicrography, R. T. Loveland —224(A)
Photographic effectiveness of the radiation from a number of photographic sources, W. E. Forsythe and M. A. Easley—310
Photographic intermittency effect in the region of extremely short flash periods, J. H. Webb—347
Photographic latent image considered from the standpoint of the quantum mechanics model of crystals, J. H. Webb—367
Photographic penetration of haze, Nora M. Mohler—219
Pressure effect on sensitivity of different photographic films, Ny Tsi-Zé, and Lü Ta-Yuan—26
Spurious photographic reciprocity defect for $\alpha$-rays, R. N. Wolfe and T. R. Wilkins—228(A)
Summation of different color radiations by a photographic emulsion, J. H. Webb—12, 228(A)
Temperature coefficient of photographic sensitivity. Part II. Effect of low temperature on the photographic action of $\alpha$-particles, S. E. Sheppard, T. R. Wilkins, E. P. Wightman and R. N. Wolfe—228(A)
Validity of the photographic reciprocity law for $\alpha$-rays, R. N. Wolfe and T. R. Wilkins—105

**Polarization**
Measurement of small retardations with the polarizing microscope, R. S. Bear and F. O. Schmitt—363
Method for making and testing quarter-wave plates, R. M. Emberson—63
Plane polarization in sunlight reflected by nonpolished surface, F. E. Wright—230(A)
Polarimetric determination of optical properties, R. M. Emberson—443
Polarizing characteristics of polaroid plates for wavelengths 4000A to 20,000A, L. R. Ingersoll, J. G. Winans and E. H. Krause—233
Polarizing vertical illuminator, L. V. Foster—224(A)
Polaroid half-shade analyzer, A. H. Pfund—453
Simple azimuth and phase half-shade of variable sensitivity, C. V. Kent—450
Transmission curves for the new polarizers, J. Strong—256

**Pyrometry**
Portable blocking-layer photo-cell pyrometer, G. F. Hubing—260

**Radiation, general, including thermal**
Second law of thermodynamics as applied to optics, E. E. Witmer—229(A)
Spectral radiant intensities of some tungsten filament incandescent lamps. B. T. Barnes and W. E. Forsythe —313

**Reflection** (see also **Methods and instruments, general**)
Estimation of gloss with a luminous target, R. S. Hunter—304(A)
Gloss investigations using reflected images of a target pattern, R. S. Hunter—190
Identification of five different types of gloss effects, R. S. Hunter—224(A)
Null method photoelectric reflectometer, R. S. Hunter—225(A)
On a method of decreasing the reflection from nonmetallic substances, J. Strong—73
Reflection and absorption of daylight at the surface of the ocean, W. M. Powell and G. L. Clarke—111

**Refraction**
On the refractive index changes in optical glass occasioned by chilling and tempering, F. Twyman and F. Simeon—121
Refraction of tempered plate glass, J. J. Hopfield and G. B. Watkins—24

**Scattering of light**
Photographic penetration of haze, Nora M. Mohler—219
Scattering of daylight in the sea, C. L. Utterback and W. Jorgensen—257

**Sources of light** (see **Light sources**)

**Spectra, general**
Spectrum of rubidium in the mercury arc, I. A. Balinkin and D. A. Wells—77

**Spectroscopy, including spectrometers**
Application of punched card equipment to the analysis of complex spectra, J. V. Atanasoff and A. E. Brandt—83

**Spectroscopy, including spectrometers** (continued)
Effect of pre-exposure in spectrum photography, D. Norman—407
Fuertes observatory ultraviolet stellar spectrograph, R. W. Shaw—273
Hyperfine structure spectrograph, L. P. Granath and R. K. Stranathan—279
Separation of close spectral lines by the method of anomalous dispersion, F. T. Holmes—365
Spectrometer for studies at high pressures, W. J. Lyons and F. E. Poindexter—146
Ultraviolet wave-length standards of N, C, and O, λ2300 to λ1080, R. L. Weber and W. W. Watson—307
Wave-length identification lists for the extreme ultraviolet, J. C. Boyce and H. A. Robinson—133

**Vision; visibility**
Aid to the calculation of tristimulus specifications, J. Razek—225(A)
Centers of ocular rotation and other characteristics of vertical and horizontal eye movements, W. R. Miles—226(A)
Correction of aniseikonia with ophthalmic lenses, K. N. Ogle—323
Dark adaptation as influenced by intensity of light adaptation, S. Hecht and C. Haig—304(A)
Effect of length of exposure of the test object on visual acuity. A correction, C. E. Ferree and G. Rand—272
Electrical studies of vision, H. K. Hartline—221(T)
Intensity, area, and distance of visual stimulus. A Correction, E. Freeman—271
Rational visibility meter, M. Luckiesh and F. K. Moss—227(A)
Saturation as the basis for color mixture in the color-blind, S. Hecht and S. Shlaer—226(A)
Theory of microscope vision, M. Herzberger—52, (erratum) 196, 221(T)